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FINAL REPORT

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Safety in Earth Orbit Study

Volume I – Technical Summary

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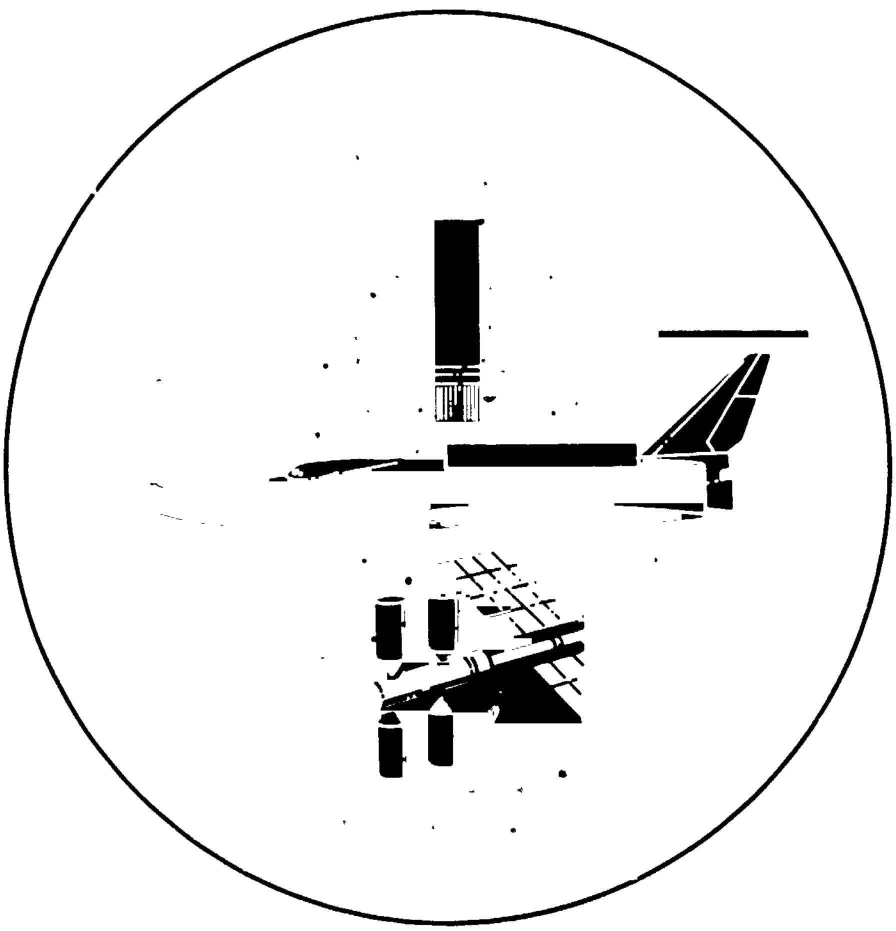

JULY 12, 1972

Space Division
North American Rockwell

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Volume I
Technical Summary

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Contract NAS9-12004

Approved by

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Study Manager

Space Division
North American Rockwell

FOREWORD

Final documentation of the Safety in Earth Orbit Study is submitted by the Space Division of North American Rockwell Corporation to the National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas, in compliance with DRL Line Items 3 and 4 of NASA-MSC Contract NAS9-12004. The study was performed for the NASA Manned Spacecraft Center by the Space Applications Program organization at the Space Division (SD) of North American Rockwell (NR). Mr. P. E. Westerfield of the Safety Office was the NASA Technical Manager.

Documentation of the study results is as shown in the following table.

DRL Line Item	Title	NR-SD Report No.
4	Contract Summary	SD 72-SA-0095
3	Final Report	
	Volume I - Technical Summary	SD 72-SA-0094-1
	Volume II - Analysis of: Hazardous Payloads; Docking; On-Board Survivability	SD 72-SA-0094-2
	Volume III - Analysis of: Tumbling Spacecraft; Escape and Rescue	SD 72-SA-0094-3
	Volume IV - Space Shuttle Orbiter Safety Requirements and Guidelines On-Orbit Phase	SD 72-SA-0094-4
	Volume V - Space Shuttle Payloads Safety Requirements and Guidelines On-Orbit Phase	SD 72-SA-0094-5

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The comments, always constructive, of Mr. H. Schaefer, NASA Headquarters, and of Mrs. R. N. Weltmann, Lewis Research Center, also significantly improved the quality and readability of the study outputs.

Personnel at North American Rockwell who participated in the study are:

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Tumbling Spacecraft	-	A. Cormack III A. N. Moore B. U. Mahr
Escape and Rescue	-	C. N. Harshbarger B. U. Mahr

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1.0 INTRODUCTION

Most of the manned spaceflight programs planned by NASA for the late 1970's and 1980's are concentrated on earth orbital operations. These will use the shuttle and a variety of manned and unmanned payloads delivered to orbit by the shuttle.

This 12-month study examined five specific safety issues associated with these operations. The study logic used is shown in Figure 1-1. The five issues were studied as five separate tasks in the order shown. Hazards analyses were used on the first three tasks only.

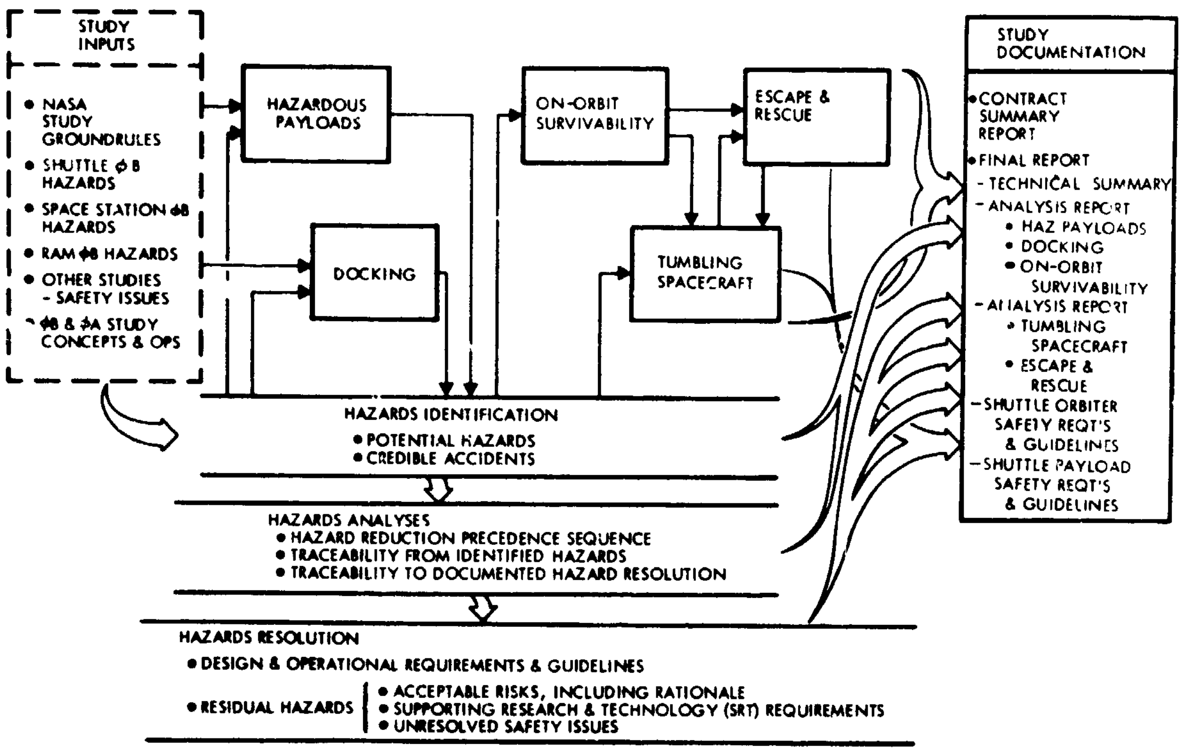


Figure 1-1. Study Logic

C

1.1 SCOPE

The study scope covered the vehicles shown in Figure 1-2.

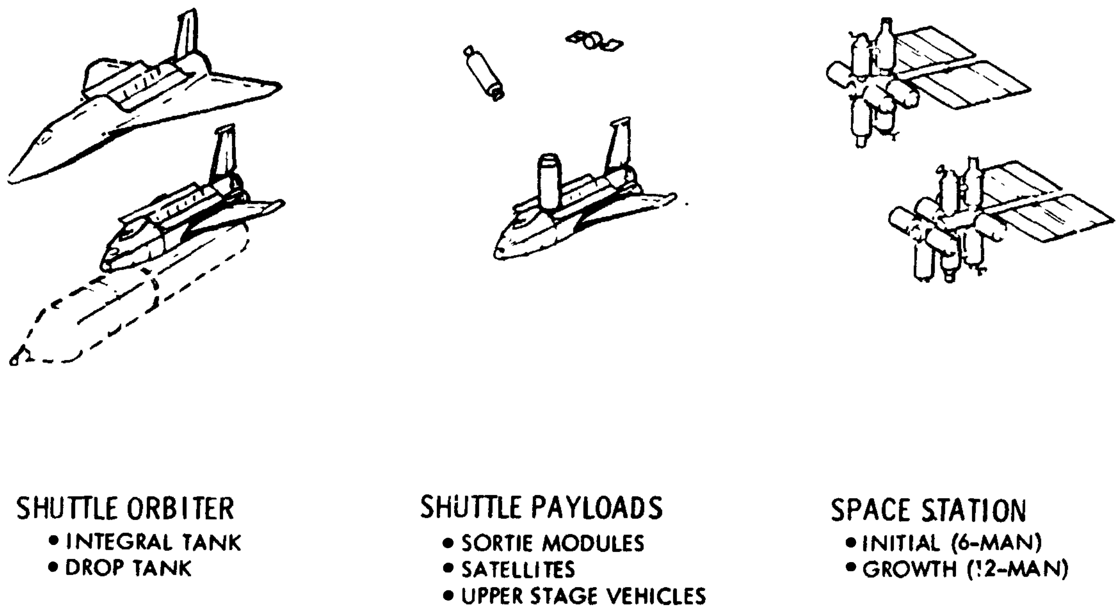


Figure 1-2. Vehicles Considered in Study

Initial tasks were based on the integral tank shuttle orbiter, but emphasis was later switched to the drop tank orbiter as this concept developed. The assumptions made were broad enough that no results were invalidated by this change.

Shuttle payloads considered included manned and unmanned sortie payloads (i.e., attached to the orbiter), satellites delivered to earth orbit, and potential upper stage vehicles, such as the tug, Agena, Centaur, etc., used to deliver unmanned payloads to orbits beyond the orbiter's capabilities.

The space stations considered were modular stations delivered to earth orbit and assembled by the orbiter. Initial 6-man versions and growth versions with up to 12 men, as defined in recent Phase B studies, were studied.

To the maximum extent possible, the analyses were performed with the minimum configuration oriented and operational assumptions possible, in order to have the results applicable over as wide a range of changes from currently planned programs as possible.

Within the scope of the vehicles described, the study is bounded by the following study ground rules:

- The main concern is personnel safety. A lesser emphasis was placed on avoiding damage to or loss of the vehicles.
- The analysis was confined to the manned on-orbit phase of missions. Launch, boost, deorbit, reentry and landing of the orbiter, or unmanned operations of the station and upper stage vehicles away from the orbiter were not considered.
- The study results cover only the specific concerns of the study. They must not be assumed to cover all safety aspects of the relevant vehicles.

1.2 STUDY OBJECTIVES

The study concerned itself with five specific issues. These issues and their objectives are:

1. Hazardous payloads. The objective was to identify hazards associated with certain orbiter payloads and to determine safety requirements and guidelines.
2. Docking. The objective was to compare a number of different approaches for docking an orbiter to a space station, and to recommend the methods preferred from a safety point of view.
3. On-board survivability. The objective was to determine the configurational and other requirements for the orbiter, sortie module and space station to allow personnel to survive on-board emergencies.
4. Tumbling spacecraft. The purpose was to determine practical means for arresting the motion of out-of-control tumbling spacecraft by external means, or to allow on-board personnel to escape from a spacecraft if tumbling cannot be arrested.
5. Escape and rescue. The objective was to determine the applicability of previous or new concepts for escape, rescue, and bail-out survivability to the orbiter, sortie modules and space station.

This volume presents a summary of the technical results and conclusions of the study. It is arranged by task, Sections 2 to 6 each covering one of the tasks, in the order in which they were performed, as shown in Figure 1-1. The complete analyses are documented in Vol. II of this report for the first three tasks and in Vol. III for the last two tasks.

1.3 RELATIONSHIP TO OTHER STUDIES

The Safety in Earth Orbit Study was perfor... . in the context of a wide range of related studies. This relationship is shown in Figure 1-3.

The most important of these studies are the Phase B studies on the space station, shuttle and RAM (Research and Applications Modules). These studies were the main sources of data on the station, shuttle and sortie module, respectively. Phase A studies on the Tug, Orbit-to-Orbit Shuttle (OOS) and the Chemical Interorbital Shuttle, and concurrent systems studies on the Orbital Operations and the In-Space Propellant Logistics (ISPLS) Studies provided additional information, both on relevant hardware elements and on operational modes.

A good interchange of information was possible with all these studies for which NR was a prime contractor (subcontractor on the RAM). The interchange of information and ideas generally flowed in both directions. This interchange was particularly fruitful with the Orbital Operations Study and the safety portion (Phase 2) of the ISPLS study.

Additional safety background was obtained from earlier safety studies by Boeing (on the space station), Lockheed (on the shuttle), and from ongoing studies by the Aerospace Corporation (on the shuttle and on escape and rescue). A particularly useful cooperative effort was also established with the Pennsylvania State University on the dynamics of tumbling spacecraft.

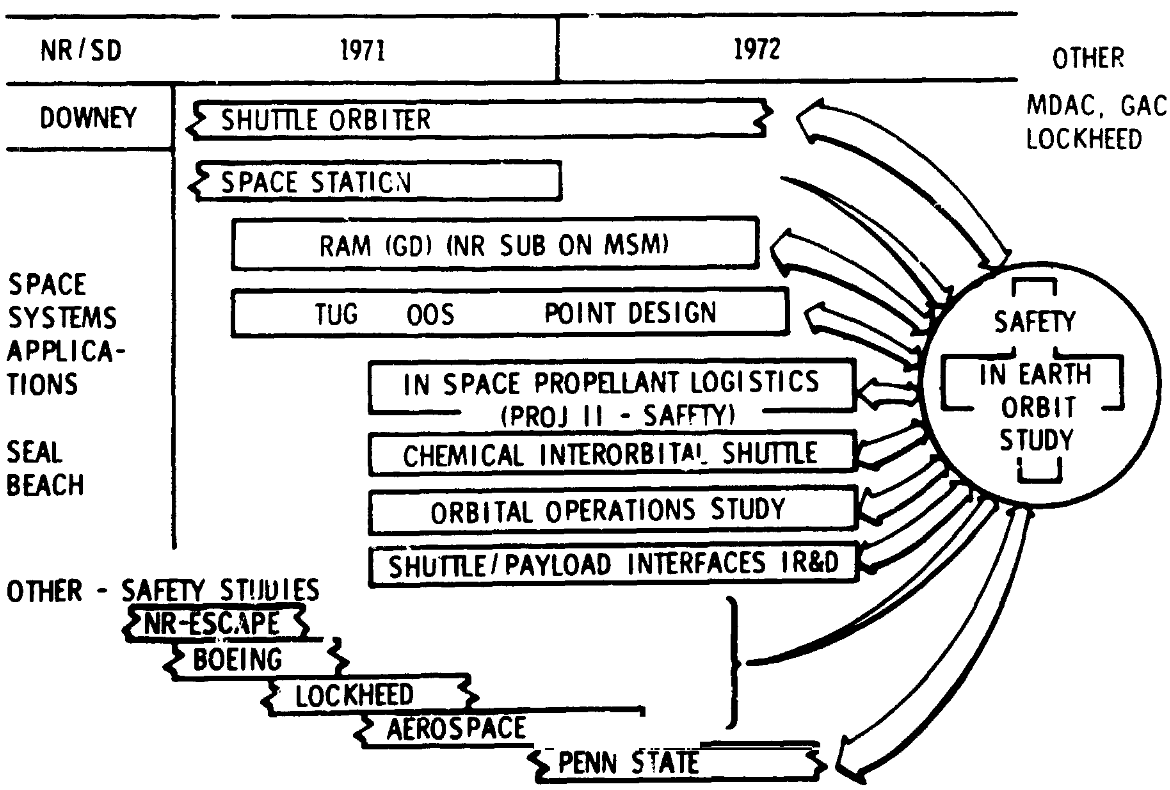


Figure 1-3. Relationship to Other Studies

1.4 BASELINE MODEL

The baseline model discussed in this section describes typical shuttle orbiter configurations, shuttle missions, and the interfaces with the shuttle payloads, sortie modules, and the space station.

While this model is typical, many variations have been or are being considered. The attempt has been made to make the results of the entire study as insensitive to the concepts, configurations, operational modes, design details, and program schedules as possible, so as not to invalidate the study as the space program evolves. This has been done by dealing with the problems parametrically, and not typing the analyses to specific designs, sizes, or missions. The description of the baseline model that follows, therefore, should be read as describing typical current concepts, and not the concepts assumed for the study.

1.4.1 Typical Shuttle Mission

A typical shuttle mission, shown in Figure 1-4, was generated from NR Phase B shuttle data to identify approximate projections of shuttle functions and timelines, and to illustrate the scope of this study within the shuttle mission. Earth orbit is interpreted for purposes of the study as encompassing that portion of the mission that starts with orbit injection and terminates with deorbit. On-orbit time can be up to 30 days.

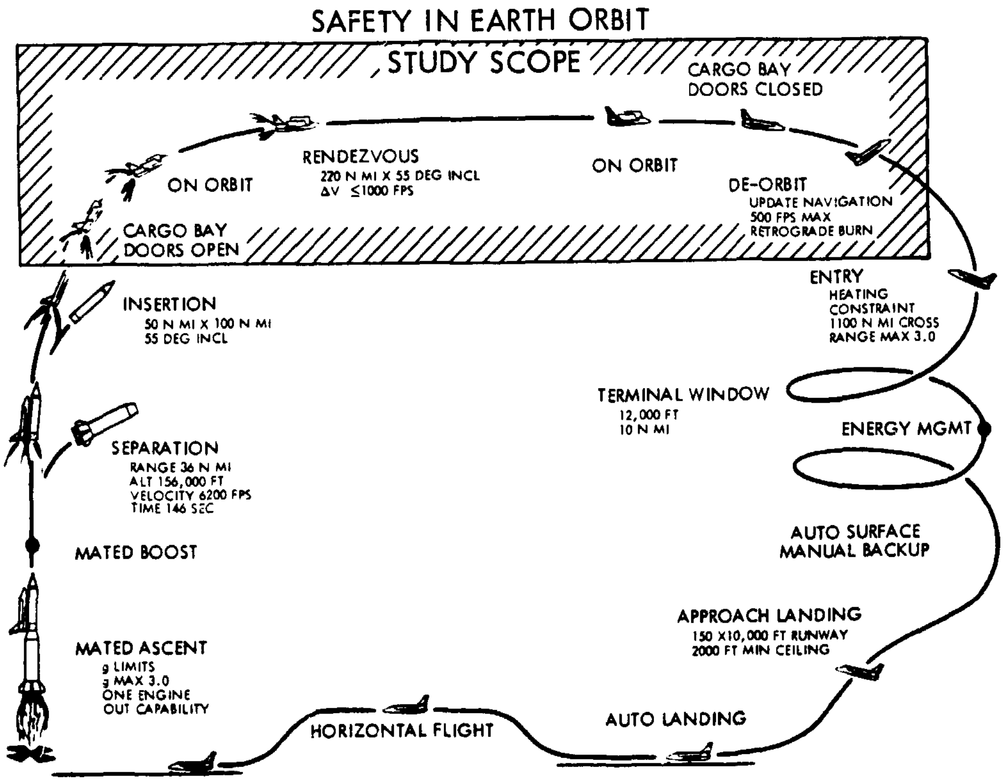


Figure 1-4. Typical Shuttle Mission

At launch (t_0) the orbiter and booster are mated and remain mated until staging, at which time separation occurs and the booster flies back to a landing site, while the orbiter initiates a main engine burn to effect injection into a 93 by 185 km (50 by 100 n mi) orbit at approximately t_0 + 9 minutes. Immediately after post-insertion checks on orbiter subsystems, the orbiter cargo bay doors are opened to expose the orbiter space radiators on the inside of the cargo bay doors to space. This occurs at approximately 9 to 40 minutes after launch. At approximately 50 minutes, the apogee of the 93 by 185 km (50 x 100 n mi) orbit is obtained and a circularization burn is performed to circularize the orbiter in the 185 km (100 n mi) phasing orbit. After initial phasing relative to the target vehicle is accomplished, rendezvous and phasing adjustments are made during a series of Hohmann transfer burns to a circular orbit approximately 18.5 km (10 n mi) below the target vehicle. Final phase adjustments are made prior to initiating the terminal phase initiation burn to complete the rendezvous, stationkeeping, and docking operations.

During the subsequent on-orbit staytime at the target vehicle orbit, the orbiter can either be attached to or can station-keep at a safe distance from the target vehicle.

Shortly before deorbit, phasing with a landing site is accomplished, system checks are made, and the cargo bay doors are closed. The deorbit burn which follows will result in entry to the earth's atmosphere at approximately 122 km (400,000 feet) and subsequent approach and landing at the preselected landing site.

It is significant to note that the orbiter cargo bay doors would be closed for only 1/2 hour to 1 hour while on orbit for a shuttle mission of any duration.

1.4.2 Typical Orbiter Model

The primary orbiter concepts considered in the study are shown in Figures 1-5 and 1-6. The integral tank orbiter concept resulting from NR Phase B shuttle studies is shown in Figure 1-6 and includes such features as a 4.6 m 15-ft-diameter by 18.3 m 60-ft-length cargo bay with hinged cargo bay doors, two manipulators with peripheral illumination, visual and operating aids, a manipulator operator station, and an airlock docking port which interfaces with the crew and passenger compartments and with a personnel transfer port leading to the cargo bay. This configuration includes integral LH_2 and LO_2 propellant tanks for the main propulsion system used for orbit injection, and the auxiliary propulsion system used for orbit maneuvering and attitude control. An air-breathing propulsion system, which employs JP fuel and turbofan engines, is incorporated to provide the capability for short-duration powered descent after vehicle entry, powered landing and go-around, and vehicle ferry operations.

The drop tank orbiter configuration resulting from NR Phase B extension studies is shown in Figure 1-6 and differs from the previous configuration primarily in that it features an external jettisonable LO_2/LH_2 ascent propellant tank, employs storable hypergolic propellants (nitrogen tetroxide and Aerozine 50) for the orbit maneuvering and attitude control systems. It is a lighter vehicle than the integral tank orbiter with a geometry which required relocation of the airlock docking port to the nose of the vehicle.

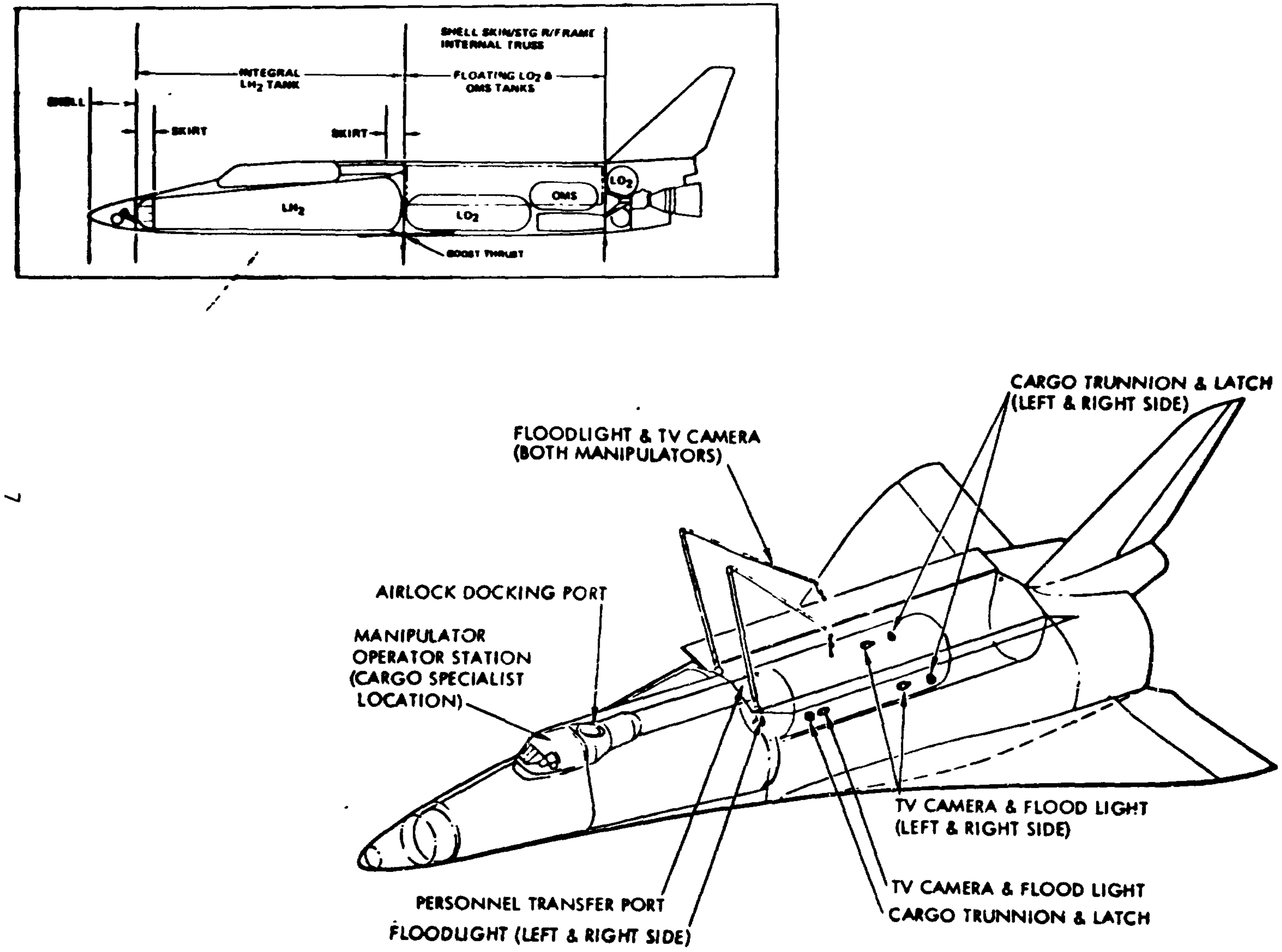
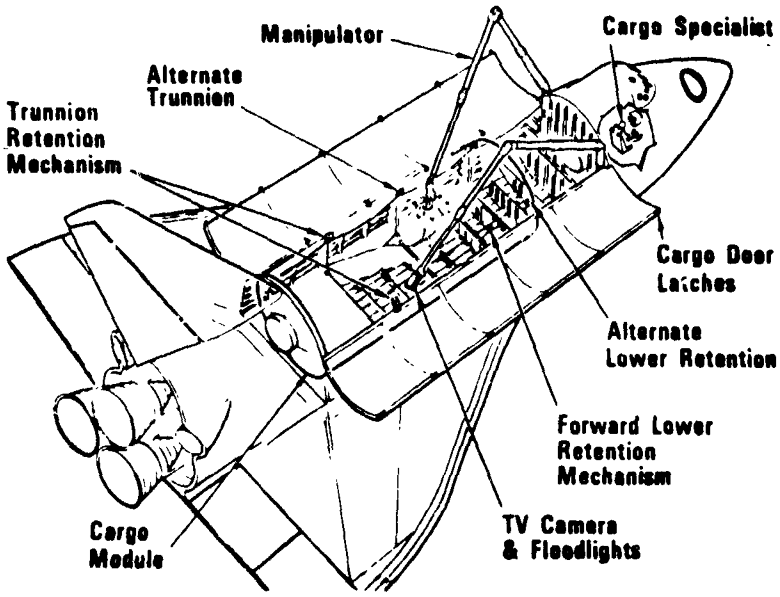


Figure 1-5. Integral Tank Orbiter Concept



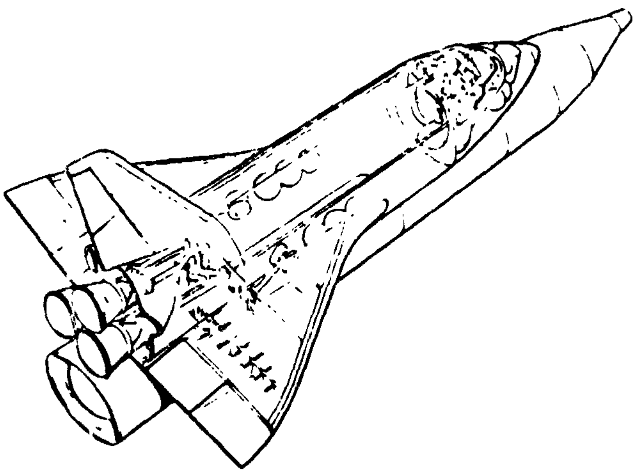


Figure 1-6. Drop Tank Orbiter Concept

The initial MDAC orbiter concept, which is similar to the NR integral tank orbiter, also employs integral LO_2 and LH_2 propellant tanks. However, a rotation payload deployment mechanism concept is used in lieu of an articulating manipulator, as shown in Figure 1-7.

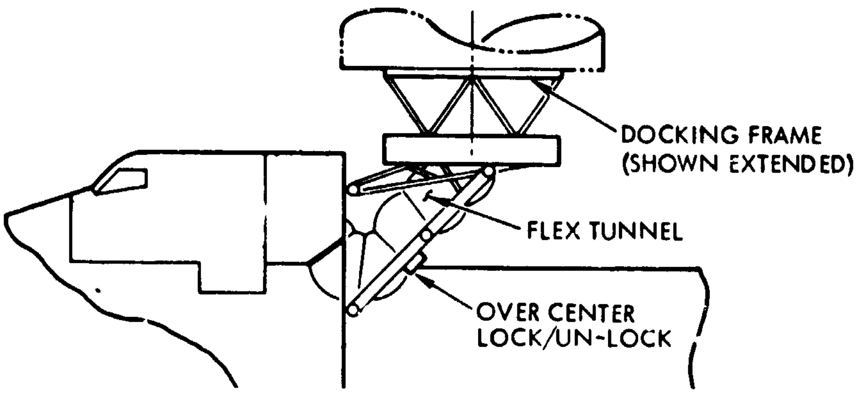


Figure 1-7. MDAC Payload Deployment Mechanism

1.4.3 Typical Orbiter Payloads

Orbiter payloads considered in the study include the following:

1. Unmanned pallet-type sortie payloads, which remain attached to the orbiter. These may remain in the cargo bay, or be deployed out of it for exposure to space.

2. Manned sortie modules, which remain attached to the orbiter. These also may remain in the cargo bay, or be deployed out of it during orbital operations. These may be flown combined with an unmanned pallet payload.

3. Automated payloads. These include satellites and subsatellites delivered to orbit by the orbiter and operate detached from the orbiter. These also can be retrieved for servicing or return to earth.

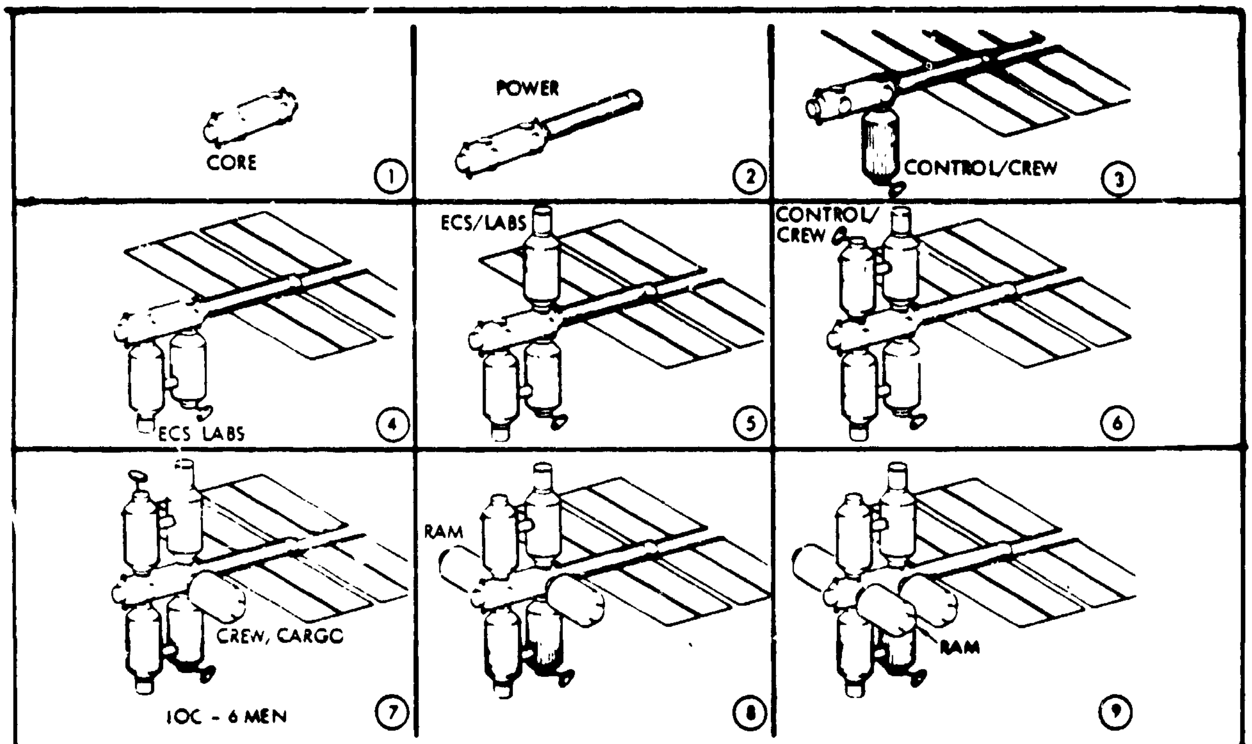
4. Upper stage vehicles with their payloads. These are used as a shuttle third stage to deliver payloads beyond the orbiter's capability. The upper stage vehicles considered as candidates include:

    - o Agena
    - o Centaur
    - o Burner II
    - o Transtage
    - o Apollo service module (SM)
    - o Tug or orbit-to-orbit shuttle (OOS)

The Centaur, tug, and OOS, and possibly the SM, are considered reusable and may be retrieved. The others are expendable. These include the modules required for buildup of the permanent station, cargo modules for logistics resupply, experiment modules, and replacement modules as required. All these modules are returnable to earth in the orbiter.

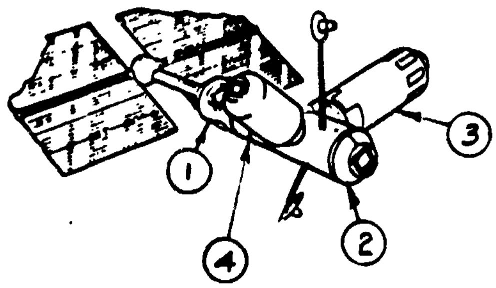
1.4.4 Typical Space Station Model

The primary modular space station (MSS) concepts being considered by NR and MDAC for the initial station are shown in Figures 1-8 and 1-9. As shown in Figure 1-8, the NR initial station consists of nine modules requiring a like number of shuttle flights for the station buildup. Similar data for the MDAC initial modular station are presented in Figure 1-9.



Launch No.	Module	Module Elements
1	Core	Power generation and conversion, IVA/EVA air-lock, guidance and control, reaction control, consumables
2	Power	Solar array, emergency hatch, GN_2, GO_2
3	Control/Crew	Control center, personal hygiene, data analysis, commander/exec stateroom isotonic exercise area, photo lab, crew stateroom, waste management equipment
4	ECS/Labs	Environmental control and life support equip-ment, nadir airlock, mechanical lab, optical/electrical lab, bioscience/earth observation laboratory
5	ECS/Labs	Environmental control and life support equip-ment, zenith airlock, galley, dining and recreation, physics/biomedical lab
6	Control/Crew	Control center, personal hygiene, medical and crew care, commander/executive stateroom, crew stateroom
7	Crew/Cargo	Crew, propellants, consumables
8	RAM	Experiments
9	RAM	Experiments

Figure 1-8. NR Modular Space Station



Launch No.	Module	Module Elements
1	Power/Subsystems	Solar array, propellant tankage, system communication, data management, displays/controls, onboard checkout, pump-down accumulator, atmosphere supply, control moment gyros, guidance and control, horizon sensor, electrical power supply, reaction control
2	Crew/Operations Module	Crew quarters, electronics, hygiene, command control console, galley/wardroom, crew quarters, food storage
3	General Purpose Laboratory	Data evaluation, secondary and experiment control consoles, airlock chamber and controls, biomedical lab, optical lab, isolation and test lab, EVA airlock, airlock chamber, mechanical sciences lab, hard data processing facility, electrical/electronics lab
4	Logistics Module	Propellant cargo, liquid and gas cargo, solid cargo, cargo handling aids, crew transfer tunnel, and airlock

Figure 1-9. MDAC MSS Buildup Sequence/Initial Station

2.0 HAZARDOUS EARTH ORBITAL SHUTTLE PAYLOADS, CARGO TRANSFER, AND HANDLING

Many different kinds of payloads will be carried into orbit in the orbiter cargo bay. The purpose of this task was to identify, analyze, and recommend solutions of the hazards resulting from (a) the delivery, deployment, and retrieval of hazardous payloads, and from (b) the transfer and handling of general types of cargo. Three particular areas of concern were investigated since they concern the safety of the orbiter and its crew and passengers while in orbit. These are:

- o Upper stage vehicles as they are transported in the orbiter cargo bay, deployed, and retrieved. These vehicles include expendable stages, mainly using storable or solid propellants, and reusable cryogenic stages. Hazards specific to on-orbit orbiter aborts are included.
- o Hazardous fluid vessels transported and off-loaded in earth orbit in the orbiter as cargo or as part of a payload. Orbiter on-orbit abort hazards are included.
- o The handling and transport of cargo between the orbiter, sortie modules, and space station.

It is believed that the assumptions inherent in this task are few and simple. These are:

- o The shuttle orbiter has the capability to operate in earth orbit independently of other vehicles in orbit, of the payload, or of the ground.
- o The orbiter has the inherent capability to return to earth with all its crew and passengers.
- o The orbiter payload or payloads are carried in a single cargo bay. This cargo bay is protected during boost and reentry by a cargo bay door or doors, which form a part of the orbiter, and can be opened and closed by the orbiter crew. The cargo bay is not pressurized or pressurizable in orbit.
- o The orbiter has the capability to deploy payloads out of the cargo bay, when required, and to retrieve and stow recoverable modules and payloads.
- o The orbiter and space station have docking capability.

So long as these assumptions remain valid, the results of this task should be applicable. In addition, assumptions applicable to specific hazards/emergency analyses have been recorded individually in the particular analyses.

2.1 CONCLUSIONS AND RECOMMENDATIONS

The main outputs of this task are the safety requirements and guidelines which result from the hazard/emergency analyses. Conclusions from this task, based on the hazard/emergency analyses and other supporting analyses, are presented in the following paragraphs.

- The orbiter design is extremely sensitive to even small explosions in the cargo bay. Uncontained explosions equivalent to as little as 5 g (0.01 lb) of TNT may result in exceeding the structural design limit of the cargo bay structure (14 kN/m^2, 2 psi) from blast overpressure. By comparison, a hand grenade is equivalent to 10 g (0.025 lb) of TNT and a fully loaded Centaur to approximately 2700 kg (6000 lb) of TNT.

- Any structural failure of a loaded upper stage vehicle while in the orbiter cargo bay which results in large leaks of both fuel and oxidizer will almost certainly be catastrophic to the orbiter.

- The emergy content of even the smallest liquid propellant upper stage vehicle, if released suddenly, is far more than can be tolerated by the orbiter. The vehicle accelerations caused by the reaction of the leaking fluids will ensure mixing, and an ignition source will almost certainly be present during the process of structural failure. A chemical reaction therefore can be expected, and this will probably propagate faster than the rate at which the fluids can disperse in space, even with the cargo bay doors open. Every effort must therefore be made to prevent structural failure of upper stage vehicles while in or near the orbiter. Remedial measures are not considered practical, and have not been recommended.

- If the leakage of large quantities of payload fluids into the orbiter cargo bay is considered credible during boost or while the orbiter is in orbit with the cargo bay doors closed, then additional venting of the cargo bay beyond that provided by the orbiter for normal venting may be required to avoid potential overpressurization of the cargo bay. This may need to be considered and provided for individually for each payload which contains large quantities of fluids.

- The chemical and physical behavior of gases, liquids, and cryogenic fluids is not well understood in the zero-g and zero or very low pressure environment encountered in space. An important area of uncertainty as to the potential effects of leaking fluids therefore exists, and the severity, or even the possibility, of hazards such as combustion, chemical reaction, corrosion, attachment of frozen gases to the structure, etc., cannot be

properly evaluated at present. In the hazard/emergency analyses in this task, the worst-case assumption was made that effects which are theoretically possible, such as sustained combustion of leaking hypergolics, will indeed occur.

- Launching a space station or sortie modules pressurized at 1 atmosphere can present the orbiter with a considerable hazard. A typical station module of 140 m^3 (5000 ft^3) volume has an explosive potential of 10 kg (22 lb) TNT equivalent. This arises because of the energy which could be released in the vacuum environment of space from the contained atmosphere. If this energy is instantaneously released, e.g., by structural failure of the module, the resulting blast and shrapnel would cause catastrophic damage to the orbiter. A rapid release of the contents of the module when the cargo bay doors are closed, without any blast effects, could still pressurize the cargo bay to about 20 kN/m^2 (3 psi), or about 50 percent above its present design limit. Rapid release of the module contents when the cargo bay doors are open, or a slow enough release so that the orbiter cargo bay vent system can adequately relieve the pressure, would not result in damage.

- Many different fluids, of varying degrees of hazard and in varying quantities, are currently planned for transportation to and from space by the orbiter and for use in sortie modules and on the space station. While many general safety requirements and guidelines have been identified, and an adequate level of safety appears possible to both the personnel involved and the spacecraft, more specific safety features than defined in this study must await a more detailed definition of the spacecraft, payloads, and their planned operations than is currently available.

- Cargo handling in space presents some specific hazards associated with the zero-g environment and with the limited remedial and escape provisions available. In addition to normal safety features required on the ground, specific requirements and guidelines, such as tethering of heavy cargo at all times, double-containing hazardous cargo, and providing mechanical assist where propulsive forces are possible, have been identified.

The main recommendations from this task are contained in the safety requirements and guidelines developed during the hazard/emergency analyses. Specific top-level recommendations arising from these and from supporting analyses are described in the following paragraphs.

- The cargo bay doors on the orbiter should be opened as early as possible and closed as late as possible while in orbit when hazardous fluids or large quantities of propellants are carried in the orbiter cargo bay. This minimizes hazards from leakage, explosions, contamination, etc.

- The liquid contents of upper stage vehicles being returned to earth should be dumped to space before deorbiting the orbiter. The purpose is to avoid the possibility of an uncontrolled increase in internal upper stage vehicle pressure during reentry

or on the ground, possibly from an unexpected heat leak. The acceptable level of residual liquids and gas before returning to earth should be such that an insulation failure, leakage, or a crash landing will not result in overpressurization, fire, or a similar accident.

- The capability should be provided for the orbiter to deorbit, reenter, and land with a fully loaded upper stage vehicle. This condition may arise from a failure to deploy the upper stage vehicle (perhaps because of lack of time following an abort situation) and failure to dump upper stage vehicle propellants. While such a combination of events may be quite improbable, the consequences could be catastrophic, and the condition should be designed for as being credible. It is not recommended that reduced factors of safety be considered for this situation, but the reentry and landing load criteria should be less severe than the normal design cases (e.g., 2σ conditions instead of 3σ) for this maximum weight condition, to avoid combining unrealistically severe worst-case design cases. The pilot in such situations will undoubtedly take extra care to avoid a hard landing.

- Upper stage vehicles must be man-compatible; i.e., man rating safety criteria must be applied to systems and functions of the upper stage vehicle which could create a hazard to the orbiter while the upper stage vehicle is in or near the orbiter. These criteria, which are not currently defined, must be defined consistently for the shuttle and for upper stage vehicles. One possibility is that a flight test of the upper stage vehicle be performed in the shuttle using fluids which are physically similar to the propellants but which do not react chemically. For example, LN_2/LH_2 may be used to simulate LO_2/LH_2. Such a flight test may be cost-effective because it can also replace much of the ground qualification testing.

- Because of the criticality to the orbiter of a failure of a pressurized sortie or space station module in the cargo bay while in space, two areas should be studied further:

  - Identify and eliminate failure modes which can cause major structural or other failures of pressurized sortie or space station modules during boost, on-orbit, and reentry phases.

  - Consider venting the modules to space while they are still in the cargo bay, to reduce the explosive potential. The necessary atmosphere can be taken up in a number of high-pressure tanks within the module. This has the effect of reducing the potential for damage, both by reducing the energy content per tank, and by reducing pressure that can be generated in expanding the gas from a ruptured tank to the cargo bay volume.

2.2 RESIDUAL HAZARDS AND HAZARDS RESOLUTION

This section summarizes the hazards identified and their resolution, and presents the resulting requirements for supporting research and technology.

2.2.1 Resolution of Identified Hazards

The disposition of the 25 hazards identified is shown in Table 2-1. This shows the judgments of the investigators as to which hazards would be resolved by implementation of the recommended requirements and guidelines, and which are residual hazards; which of the residual hazards represent acceptable risks; and which require supporting research and technology (SRT) or must at present be considered unresolved safety issues.

2.2.2 Supporting Research and Technology Requirements

The supporting research and technology requirements resulting from the areas of uncertainty of this task are listed below (the main originating hazards/emergency are indicated in parenthesis):

- The behavior of pressurized cryogenics, gases, and liquid as they explode into vacuum or into a large evacuated container should be understood. The purpose would be to determine the explosive contents under different conditions and the damage that can result. The subject can initially be studied analytically and the key results verified by laboratory tests (1.1001, 1.2.005).

- Current and new techniques for designing, constructing, and operating tanks which can fail under pressure without producing shrapnel should be pursued (1.1001, 1.2.005).

- The use of strain measurements on pressurized tanks should be explored as a means of detecting impending failures on the tanks. This method has the potential advantage over conventional methods of monitoring temperatures and pressures of the contents that it can detect failures of the tank due to imperfections or weaknesses of the tank, as well as overpressurization (1.1.001, 1.2.005).

- The potential for chemical combination of mutually reactive fluids and decomposition of monopropellants in zero-g and low to zero pressure environment should be investigated to evaluate how severe this hazard is. Some insight can be gained by theoretical studies, but full confidence would require small-scale laboratory tests in simulated or actual zero-g conditions. For monopropellant decomposition, the catalytic effect of different spacecraft materials should be investigated, as well. This would require valid pressures, temperatures, and concentrations, but the zero-g environment could probably be dispensed with except as a final verification (1.1.002 and 1.1.003).

Table 2-1. Hazards Resolution

Hazard No.	Hazard	Resolved	Residual	Acceptable Risk	SRT Requirements	Unresolved Safety Issue
1.1.001	Explosion/rupture of a pressurized container in an upper stage vehicle inside or near shuttle.		X		X	X
1.1.002	Combination of mutually reactive upper stage vehicle fluids in explosion or fire inside or near shuttle.		X		X	X
1.1.003	Detonation of explosive charge on upper stage vehicle inside or near shuttle.	X				
1.1.004	Rapid decomposition of mono-propellants located in or leaking from the upper stage vehicle while inside or near shuttle.		X		X	
1.1.005	Uncontrolled combustion in active upper stage vehicle reaction control engines while near the shuttle.	X				
1.1.006	Leakage of corrosive fluids from upper stage vehicle tanks while inside the orbiter.		X		X	
1.1.007	Inadvertent start of an upper stage vehicle rocket engine while inside shuttle cargo bay.		X	X		
1.1.008	Inadvertent separation of any part of upper stage vehicle while attached to the shuttle.		X	X		
1.1.009	Loss of attitude/translation control of upper stage vehicle upon release from shuttle.		X	X		
1.1.010	Hangup of upper stage vehicle during release from shuttle.	X				

Table 2-1. Hazards Resolution (Cont)

Hazard No.	Hazard	Resolved	Residual	Acceptable Risk	SRT Require-ments	Unresolved Safety Issue
1.1.011	Rupture of common bulkhead tanks in upper stage vehicles while in or near shuttle.		X	X		
1.1.012	Loss of pressurization in pressure stabilized upper stage vehicle		X	X		
1.1.013	Inability to dump propellants of pressurants in retrieved	X				
1.1.014	Inability to dump upper stage vehicle propellants or pressurants during shuttle abort.	X				
1.1.015	Inability to close cargo bay doors after retrieval of upper stage vehicle because of interference with upper stage vehicle.		X	X		
1.2.001	Exposure of the shuttle crew or passengers to a toxic environment released from a vessel in the payload containing a toxic fluid.		X	X		
1.2.002	A fire in the cargo bay resulting from release and ignition of a flammable fluid in an unpressurized paylaod.		X		X	
1.2.003	A fire in a pressurized payload in the cargo bay resulting from release and ignition of a flammable fluid.		X		X	
1.2.004	A corrosive environment in the shuttle cargo bay resulting from leakage or rupture of a payload vessel containing a corrosive fluid.		X		X	

Table 2-1. Hazards Resolution (Cont)

Hazard No.	Hazard	Resolved	Residual	Acceptable Risk	SRT Requirement	Unresolved Safety Issue
1.2.005	An explosion in the shuttle cargo bay of a potentially explosive payload vessel.		X		X	X
1.3.001	Spillage or leakage of hazardous fluid or material during manual transfer in pressurized modules.		X		X	
1.3.002	Spillage or leakage of hazardous fluids or materials during mechanically assisted or remote transfer in pressurized modules.		X		X	
1.2.003	Spillage or leakage of hazardous fluid or material during remote transfer in unpressurized area.		X	X		
1.3.004	Failure of transfer mechanism and/or loss of control of cargo during transfer in pressurized or unpressurized areas.	X				
1.3.005	A radioactive environment in a sortie module or space station, resulting from exposure or escape of radioactive material during ransfer and handling of radioactive materials.		X	X		

- The behavior of corrosive fluids in zero g should be investigated to determine how serious the hazard of a leaking corrosive fluid could be, and to determine practical protection methods and remedial measures. Means for detecting the location of the corrosive fluid or of the corrosive action should also be investigated. This research should cover the range of pressures from full spacecraft pressures down to a vacuum. A particular point to be investigated should be the behavior of corrosive fluids which are frozen in a space environment and thaw out and become more active upon return to an earth environment (1.1006, 1.2.004).

- The flammability and chemical reactivity of spacecraft and payload materials under low pressure conditions representative of fluid leakage into the orbiter cargo bay should be investigated. The reactive gases should be fluids such as oxygen, hydrogen, N_2O_4, etc., which may be carried as propellants, cargo, or experiment fluids. The purpose would be (a) to understand the mechanics and dynamics of chemical reactions under zero-g and low-pressure conditions, and (b) to map areas of flammability and reactivity in terms of materials, pressures, temperatures, etc., for use as a guide in material selection for forthcoming spacecraft (1.2.002).

- Means for detecting and suppressing fires in a zero-g pressurized environment should be investigated. This research should include understanding of ignition, heat transfer, and flame propagation; effects of air currents due to forced convection and low-g acceleration; and the convection effects of applying fire extinguishers to the fire. Both manned and unmanned situations should be considered. The investigation should consider a broad systems approach to the problem so as to lead to practical recommendations for space applications. Tests should be considered for the Skylab program to supplement the current proposed effort (1.2.003).

- Means should be developed for locating spilled hazardous fluids and materials in a zero-g manned environment and for neutralizing or collecting and disposing of these (1.3.001, 1.3.002).

2.3 UPPER STAGE VEHICLES AS SHUTTLE PAYLOADS

The purpose of this subtask was to identify the hazards associated with the transportation, deployment, and retrieval in earth orbit of upper stage vehicles, and to determine the safety measures required to deal with these. Both expendable stages and reusable stages were considered. The orbiter on-orbit abort hazards subsequent to these types of payloads were also analyzed.

A large range of upper stage vehicles, identified below, is currently being considered for use in the shuttle orbiter. These stages will be used to launch unmanned payloads into higher orbits than the orbiter capability.

2.3.1 Hazardous Elements of Upper Stage Vehicles

The upper stage vehicles considered in this subtask were:

- o Agena
- o Centaur
- o Transtage
- o Burner II
- o Apollo service module
- o Orbit-to-orbit shuttle (OOS)/tug

It is believed that the hazards identified from these vehicles are typical of all upper stage vehicles that may be carried in the shuttle orbiter in the foreseeable future. The modified versions of the Agena and the Centaur as presently conceived differ only in the sizing of the tanks. The subsystems will be the same as on the current stages. The OOS and the tug at the time this report was prepared were in Phase A definition and therefore exact data on the subsystems to be used are not available. However, the results of the Phase A studies at North American Rockwell indicate that the OOS/tug hazards are fully covered by the other vehicles considered.

Hazardous elements of the upper stage vehicles considered are listed in Table 2-2.

2.4 HAZARDOUS FLUID VESSELS AS SHUTTLE PAYLOADS

In general, hazards exist either because the fluid is inherently hazardous, e.g., toxic or corrosive, or because of the conditions under which it is transported; e.g., at high pressure or as a cryogen. The shuttle crew or passengers are normally only directly exposed to the hazard when a manned pressurized experiments module is carried on the orbiter as part of a sortie module. Situations in which crew or passengers have exposed themselves to the hazardous fluids in extravehicular activity (EVA) have also been considered. The main safety concern has turned out to involve damage to the orbiter, particularly the cargo bay area; and this, of course, jeopardizes personnel safety indirectly by precluding return to earth.

A major area not covered in this study is the transportation into space by the shuttle of large quantities of propellants for logistic resupply of such vehicles as a tug, orbital propellant depot, and chemical or nuclear propulsion stages. The reason is that the entire subject of logistics resupply of propellants and propellant transfer is being studied in a concurrent NASA study at the Space Division, In-Space Propellant Logistics and Safety Study, Contract NAS8-27692. Project II of this study is specifically concerned with the safety aspects.

Table 2-2. Hazardous Elements of Upper Stage Vehicles

	Agena	Centaur	Transtage	Burner II	SM	OOS/Tug
Fluid Propellants:						
Nitrogen Tetroxide			X		X	
Aerozene -50			X		X	
Hydrogen Peroxide		X		X		
Liquid Oxygen		X			X	X
Liquid Hydrogen		X			X	X
Monomethyl Hydrazine					X	
Water/Glycol					X	
Unsymmetrical Dimethyl Hydrazine	X					
Inhibited Red Fuming Nitric Acid	X					
Pressurized Containers:						
Helium Tanks	X	X	X		X	X
Nitrogen Tanks	X		X	X	X	
Nitrogen Tetroxide Tanks			X		X	
Aerozene -50 Tanks			X		X	
Hydrogen Peroxide Tanks		X		X		
Liquid Oxygen Tanks		X			X	X
Liquid Hydrogen Tanks		X			X	X
Monomethyl Hydrazine Tanks					X	
Water/Glycol Tanks					X	
Unsymmetrical Dimethyl Hydrazine	X					
Inhibited Red Fuming Nitric Acid	X					
RCS Propellants:						
Aerozene -50 + Nitrogen Tetroxide			X			
Monomethyl Hydrazine + Nitrogen Tetroxide					X	
Hydrogen Gas + Nitrogen Tetroxide						X
Corrosive Fluids:						
Nitrogen Tetroxide			X		X	
Hydrogen Peroxide		X		X		
Liquid Oxygen		X			X	X
Inhibited Red Fuming Nitric Acid	X					

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Table 2-2. Hazardous Elements of Upper Stage Vehicles (Cont)

	Agena	Centaur	Transtage	Burner II	SM	O.S/Tug
Pyrotechnics:						
Connections Between Modules - Cutters					X	
Helium Valves	X		X			
Solid Propellant Igniters				X		
Turbine Start Solid Propellant Charges	X					
Explosive Bolts - Payload Separation	X	X	X	X	X	X
Linear Shaped Charge - Panel Separation	X	X			X	
Destruct Shaped Charges	X	X	X	X	X	X
External Extensions - Antennae					X	
Rocket Engines: (Qty. Indicated)						
Main Engine	1	2	2	1	1	1-4
RCS Engine		8	12	4	16	20
Stability Source:						
Gyro Reference	X	X		X		X
Accelerometers	X	X				
Computer/Flight Control	X	X		X		X
Attachment Methods:						
Explosive Bolts				X		
Linear Shaped Charge	X	X	X		X	
Not Defined						X
Attitude Hold/Translation Capabilities:						
Translation - Main Engine	X(1)*	X(1)	X(1)	X(1)	X(1)	X(1)
-RCS			X(1)	X(2)	X(6)	X(6)
- Auxiliary		X(1)				
Attitude Hold - RCS Couples					X	X
- Off-Center	X	X	X	X		
* ( ) Number of directions						

The following section identifies hazardous fluids involved in the orbiter payloads (except upper stage vehicles).

2.4.1 Hazardous Experiment Fluids

Hazardous experiment fluids were identified by a review of Volumes II through VIII of the "Blue Book", (Ref. 1). This document was selected because it is used as a baseline NASA document to define a manned space-flight research capability to be conducted in earth orbital space stations and shuttles and is therefore not oriented specifically to any single program.

The results of the Blue Book review are summarized in Table 2-3.

2.4.2 Hazardous Sortie Module Fluids

Sortie modules include research and applications module (RAM), RAM support module (RSM), mission support module (MSM), and palletized experiment payloads which remain attached to the orbiter and are used as reusable space laboratories or support facilities.

For a typical seven-day experiment sortie mission, it will require fluids in the approximate quantities and with approximate container characteristics as listed in Table 2-4.

Hazardous fluids other than those applicable to sortie missions which were identified during review of the 1971 NASA Experiment Blue Book were not identifiable.

2.4.3 Hazardous Station Fluids

Hazardous fluids are required by both the SD and McDonnell Douglas (MDAC) designs of the modular space stations during the station buildup and normal operations phases. Station modules containing hazardous fluids for attitude control, electrical power generation, and pressurization will be delivered by the shuttle during the buildup phase. Resupply of station subsystem consumables will be accomplished under the present concepts via an orbiter delivered cargo or logistics module.

The SD station is planned to generate GO_2 and GH_2 by water electrolysis during normal operations. During buildup, it requires delivery of high-pressure gases on the initial modules to support subsequent buildup operations. After station buildup, delivery of water for electrolysis and GN_2 for atmosphere leakage makeup via the cargo module will be the primary station subsystem resupply fluids. The expected fluid quantities, tank quantities, and pressures for the SD station core and power module buildup launches and the cargo module resupply for station subsystems are shown in Table 2-5. This includes fluid quantities required for station repressurization, EVA support, and 48-hour emergency support.

Table 2-3. Summary of Hazardous Fluid Vessels in Orbiter Payloads

HAZARDOUS FLUID	HAZARD				PROGRAM ELEMENT																
					UPPER STAGE VEHICLE						BLUEBOOK EXPERIMENT							OTHER			
	Toxicity	Fire	Corrosion	Explosive	Agena	Centaur	Burner II	Transtage	Service Mod./Apollo	OOS/Tug	Astronomy	Physics	Earth Observation	Comm./Nav.	Mater. Sci. & Proc.	Technology	Life Sciences	Space Station (NR)	Space Station (MDAC)	RAM Support Module	Automated Payload
CRYOGENICS																					
LN_2	B												X			X	X			X	
LO_2	B	X	X	X		X			X	X							X			X	
LH_e	B										X	X									
LH_2	B	X		X		X			X	X						X				X	
Slush Hydrogen	B	X		X												X					
Solid Cryogen	B										X										
Undefined Cryogen	B												X			X					
LN_e	B										X										
LA_r	B												X								
Superfluid Helium	B											X									
Dry Ice (LCO_2)	B																X				
GAS																					
O_2	X	X	X	X								X			X	X	X	X	X		
N_2	A				X		X	X	X			X				X		X	X	X	X
H_2	X	X		X														X			
Unspecified Gas											X					X					
H_e	A				X	X		X	X			X				X					
Hydrocarbons	X	X										X									
Carbon Tetraflouride (CF4)	X											X									
Carbon Monoxide (CO)	X	X		X								X									
Carbon Dioxide (CO_2)	A											X							X		
Nitric Oxide (NO)	C		X									X									
Acetylene ($HC \equiv CH$)	A	X		X								X									
Diborane (B_2H_6)	X	X		X								X									
Xenon (X_e)	C											X									

Footnotes: A = Simple asphyxiant
B = Can cause severe burns and tissue damage on contact with skin
C = Extremely toxic when heated to decomposition
X = Applicable or present

Table 2-3. Summary of Hazardous Fluid Vessels in Orbiter Payloads (Cont)

HAZARDOUS FLUID	HAZARD				PROGRAM ELEMENT: UPPER STAGE VEHICLE						BLUEBOOK EXPERIMENT							OTHER			
	Toxicity	Fire	Corrosion	Explosive	Agena	Centaur	Burner II	Transtage	Service Mod./Apollo	OOS/Tug	Astronomy	Physics	Earth Observation	Comm./Nav.	Mater. Sci. & Proc.	Technology	Life Sciences	Space Station (NR)	Space Station (MDAC)	RAM Support Module	Automated Payload
GAS (Continued)																					
Sulfur Hexaflouride (SF_6)	C											X									
Methane (CH_4)	A	X		X												X					
Propane ($CH_3CH_2CH_3$)	X	X		X												X					
Unspecified Combustibles		X														X					
Hydrogen Sulfide (H_2S)	C	X		X																	
LIQUID																					
Hydrazine (N_2H_4)	1	X	X	X								X				X			X		X
Nuclear Emulsion		.										X									
Hydrocarbons	X	X										X									
Trimethlaluminum ($AL(CH_3)_3$)	X	X		X								X									
Freon	X											X				X					
Mercury	X											X									
Phenol (C_6H_5OH)	X	X													X						
Formaldehyde	X	X		X											X						
Liquid Metals															X						
Potassium Sodium Niobate															X						
Potassium Sodium Silicate Solvent															X						
Gallium Arsenide Solution	X	X		X											X						
Liquid Gallium	X														X						
Fused Silicate Solutions															X						
Hexane ($CH_3(CH_2)_4CH_3$)	X	X		X												X					
Methanol (CH_3OH)	X	X		X												X					
Pentane ($CH_3(CH_2)_3CH_3$)	X	X		X												X					
Ethanol (CH_3CH_2OH)	X	X		X												X					
Freon II	X															X					
Freon II4B2	X															X					
Freon 21	X															X					
Glycol	X	X		X												X					

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Table 2-3. Summary of Hazardous Fluid Vessels in Orbiter Payloads (Cont)

HAZARDOUS FLUID	HAZARD				PROGRAM ELEMENT: UPPER STAGE VEHICLE						BLUEBOOK EXPERIMENT							OTHER			
	Toxicity	Fire	Corrosion	Explosive	Agena	Centaur	Burner II	Transtage	Service Mod./Apollo	OOS/Tug	Astronomy	Physics	Earth Observation	Comm./Nav.	Mater. Sci. & Proc.	Technology	Life Sciences	Space Station (NR)	Space Station (MDAC)	RAM Support Module	Automated Payload
LIQUID (Continued)																					
IITRI ZNO Silicone (S-13)	X	X														X					
IITRI ZNO Silicate (Z-9)	X	X														X					
LMSC Thermatrol T_LO_2 Silicone (CA-100)	X	X														X					
Schteldahl GT-.015	X	X														X					
Lubricants	X	X														X					
Hydroquinones	X	X		X																	
C_2H_4		X																			
Nitrogen Tetroxide (N_2O_4)	X		X		X			X	X												X
A-50 (50% UDMH + 50% Hydrazine)	C	X	X	X	X			X	X												X
Hydrogen Peroxide (H_2O_2)	X	X	X	X		X	X														X
Monomethyl Hydrazine	C	X	X	X					X												X

Table 2-4. RAM Support Module Fluids for Seven-Day Mission

Fluid	Fluid Quantity kg (lb)	Container Volume m^3 (ft^3)	No. of Containers
LO	310(680)	0.23 (7.1)	2
LH	34(75)	0.36 (12.6)	2
LN_2	60(133)	0.23 (8.1)	1
GN_2	4.5(10)	Not defined	Not defined

Table 2-5. Expected Hazardous Fluids - NR Modular Station Subsystems

	CORE MODULE			POWER MODULE			CARGO MODULE		
	Container Characteristics			**Container Characteristics**			**Container Characteristics**		
Fluid	Fluid Qty kg(lb)	Qty	Vol m^3(ft^3)	Fluid Qty kg(lb)	Qty	Vol m^3(ft^3)	Fluid Qty kg(lb)	Qty	Vol m^3(ft^3)
GO_2	146(322)	4	0.15(5.3)	125(274)	3	0.15(5.3)	88(194)	2	0.31(10.9)
				88(194)	3	0.31(10.9)	64(141)	1	0.22(7.9)
GH_2	18(40)	4	0.31(10.9)	15(34)	3	0.31(10.9)	3.2(7)	3	0.21(7.6)
GN_2				58(127)	3	0.24(8.6)	73(161)	6	0.31(10.9)
All pressures 2.06×10^7 N/m^2 (3000 psi).									

2.5 CARGO HANDLING AND TRANSPORTATION BETWEEN SHUTTLE ORBITER, SORTIE MODULES, AND SPACE STATION

The purpose of this subtask was to identify the hazards associated with the handling and transportation of cargo between the shuttle orbiter, sortie modules, and space station in earth orbit, and to determine the safety requirements and guidelines to deal with these hazards.

Table 2-6 shows the cargo that is needed for space station operations, including hazardous cargo. The cargo that has to be transferred between the various spacecraft in the mission model are shown in Table 2-7.

Table 2-6. Space Station Logistics Resupply

Cargo Item	Cargo Item
* Liquid hydrogen	Film-35 mm cine
* Liquid oxygen	Film-70 mm
* Liquid nitrogen	Film-150 mm
* Liquid helium	Film-225 mm
* Miscellaneous cryo	Film 16 mm
* Atmosphere	Film-9 x 14 mm
* Argon	Cultures (food)
* Neon	Specimens and food
* Helium	Food (animals)
* Carbon dioxide	Tape, video
* Oxygen	Tape, audio
* Nitrogen	Tape and microfilm
* Calibration gas	Magnetic tapes
* Miscellaneous cryo	Specimens spares
Water-animals	Logistics
Water-no metallic content	Micrometeroid collector
Water-sterile triple distilled	Ballooms
Photo process chemicals	Dry samples
Emulsion	Diary, logistics
Chemicals	Lab supplies
Film-35 mm	Physiological Measurement supplies
* Hydrazine	Accessories
Life support	Film plates
Service items	Probes
Station spares	Waste (return)
* Hazardous Items	

Table 2-7. Cargo Handling and Transfer Model

	EOS+ Crew Compartment or Airlock	*EOS+ Propellant Tanks / RAM Support Module	Experiment Pallet	RAMx (7-30 day sortie)	RAMx (free flyer)	Space Station	Space Station Cargo Module	Mission Support/ Adapter Module	Upper Stage Vehicle	USV° Payload	EOS+ Serviceable Automated Payload
EOS+ Crew Compartment or Airlock	-	-N	N	N	N	N	N	N	-	-	N
*EOS+ Propellant Tanks	-	--	H	H	H	H	H	H	H	H	H
RAMx Support Module	N	--	N,H	N,H	N,H	-	-	-	-	-	-
Experiment Pallet	N	-N	-	-	-		-	-	-	-	-
RAMx (7-30 Day Sortie)	N	-N	-	-	-	-	-	-	-	-	-
RAMx (Free Flyer)	N	-N	-	-	-	-	-	-	-	-	-
Space Station	N	--	-	-	-	-	N	-	-	-	-
Space Station Cargo Module	N	--	-	-	-	N,H	-	-	-	-	-
Mission Support/ Adapter Module	N	H-	N,H	-	-	-	-	-	** N,H	-	** N,H
USV° (Upper Stage Vehicle)	N	--	-	-	-	-	-	N	-	N,H	-
USV° Payload	N	--	-	-	-	-	-	-	N	-	-
EOS+ Serviceable Automated Payloads	N	--	-	-	-	-	-	N	-	-	-

Legend: N = Non-hazardous cargo (film, tape, service items)
H = Hazardous cargo (propellants, hazardous fluids and materials)
- = Not applicable or no cargo transfer

Notes:
* Considers potential payload use of EOS reserve propellants
** Considers potential use of EOS propellants stored in cargo bay to extend EOS capability
\+ EOS = Earth Orbital Shuttle (orbiter)
x RAM = Research Applications Module (sortie module)
° USV = Upper Stage Vehicle

Potential hazards which can occur during cargo handling and transfer operations were identified by considering possible combinations of the following:

- o Candidate cargo, both hazardous and nonhazardous
- o The cargo handling and transfer model
- o The different methods of cargo handling and transfer

The hazards or emergencies were considered to arise from two source, as follows:

- o Failures or accidents related to hazardous cargo items in otherwise normal handling and transfer operations

- o Malfunctions, failures, or accidents related to the cargo handling and transfer mechanisms, including human errors, considering both hazardous and nonhazardous cargo

Maximum Safe Tank Contents

Gaseous leakage from a pressurized tank into the orbiter cargo bay cannot be allowed to overpressurize the bay. The resulting damage to the shuttle structure and cargo bay doors could, in extreme cases, cause loss of the entire vehicle, including the crew, during reentry. Limiting the gaseous contents of any one tank to the value shown for a typical case in Figure 2-? will prevent overpressure in the event of rupture. This result takes advantage of the decrease in gas temperature during expansion to allow high initial tank pressures in relatively small tank volumes. The final low temperature reduces the immediate specific volume, so that a larger weight of gas is acceptable to the shuttle structural strength. It is therefore better, from the point of view of potential cargo bay overpressurization, to transport large quantities of gas in the orbiter cargo bay at high rather than low pressure (assuming the same storage temperature).

For example, a typical space station module contains 156 m^3 (5500 ft^3) of air at 10^5 N/m^2 (14.7 psi). This point is on the unsafe side of the curve, i.e., a massive leak from the module could damage the orbiter cargo bay. If the same quantity of air is stored in a tank of 1.56 m^3 (55 ft^3) at a pressure of 10^7 N/m^2 (1470 psi), and the module is now vented to space during launch and only pressurized after station assembly, a rupture of the tank will not now overpressurize the cargo bay, as shown by the fact that this point now lies on the safe side of the curve.

Maximum Safe Tank Contents - Liquid

Safe liquid content of upper stage vehicle tanks is a function of the amount of gas generated when liquid leakage occurs. Storable propellants release a small amount of gas because of rapid solidification. The difference between solidification temperature and normal operating temperature is small and the heat lost through evaporation is large, e.g., one pound of water at 21°C (70°F) requires only 0.073 kg (0.16 lb) of water evaporation to freeze. In contrast, cryogenic propellants vaporize a larger percentage of

the liquid before the remainder is solid; e.g., at least 25 percent for hydrogen and 53 percent for oxygen. Expansion to a higher pressure than vacuum may result in a decrease in the amount of gas generated, but at a higher temperature. Specific analysis is required for each combination of liquid and storage conditions to identify safe liquid tanks volumes.

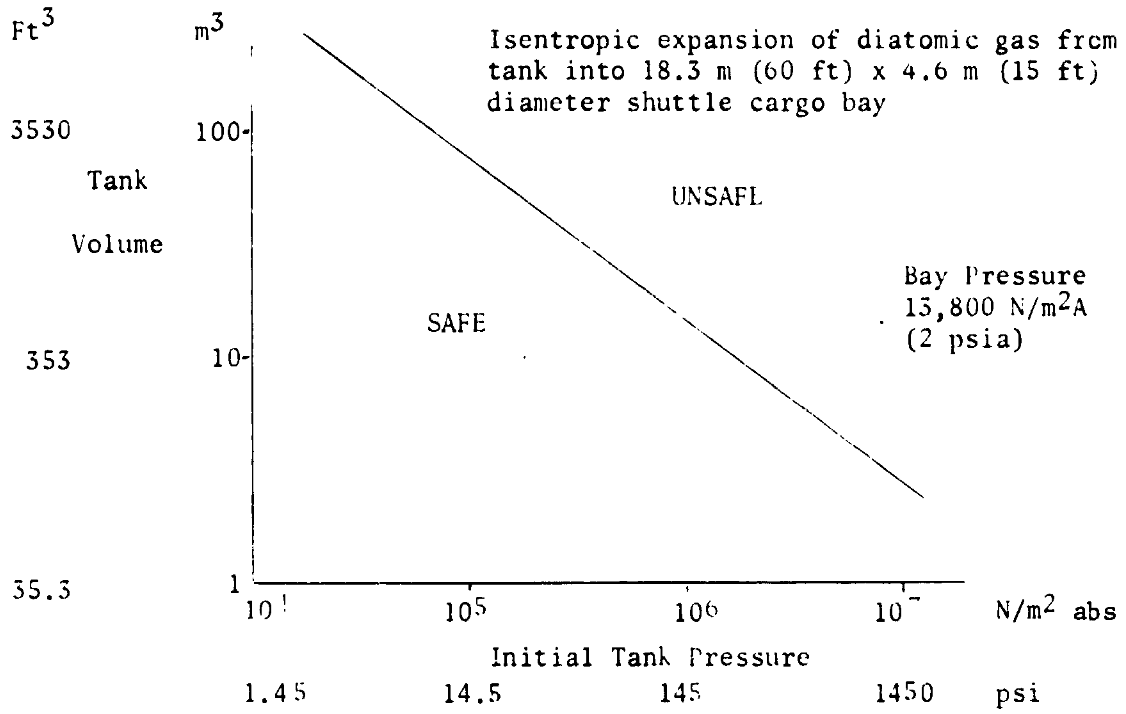


Figure 2-1. Safe Content of Gas Tanks

The TNT equivalent of hydrogen (parahydrogen) as it expands from typical subcritical conditions to vacuum is shown in Figure 2-2, as being typical of cryogenic fluids. This is plotted against the temperature of the fluid. The initial conditions on the right all represent different combinations of temperature and pressure, with the fluid fully saturated; i.e., 100 percent gas for the two top curves, and 100 percent liquid for the two bottom curves. The four curves are characterized by the entropy, which is assumed to remain constant during expansion. The variation of the corresponding "quality", or proportion of gas, during the expansion is shown for the four curves in Figure 2-3.

If the expansion starts or terminates at pressures and temperatures within the range shown in Figure 2-2, the TNT equivalent of the expansion is represented by the difference in ordinates for the two points. Since in practice, expansions of interest neither proceed to a vacuum, nor proceed isentropically, it is seen that the curves indicate the maximum potential TNT equivalent (remembering that entropy can only increase during a real process, not decrease).

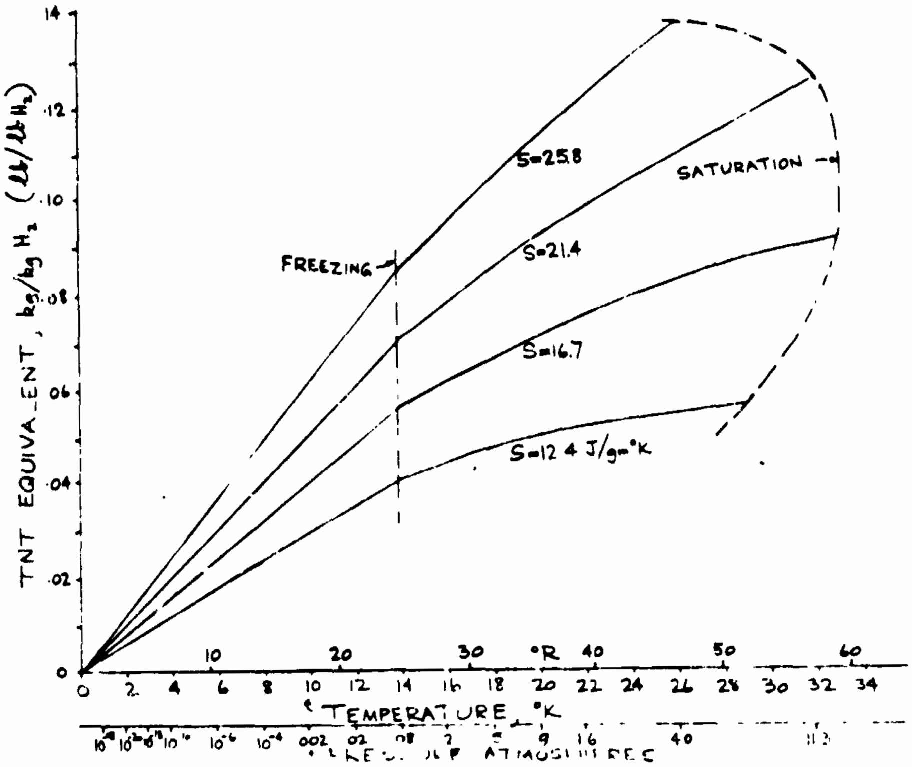


Figure 2-2. TNT Equivalent of Cryogenic Hydrogen

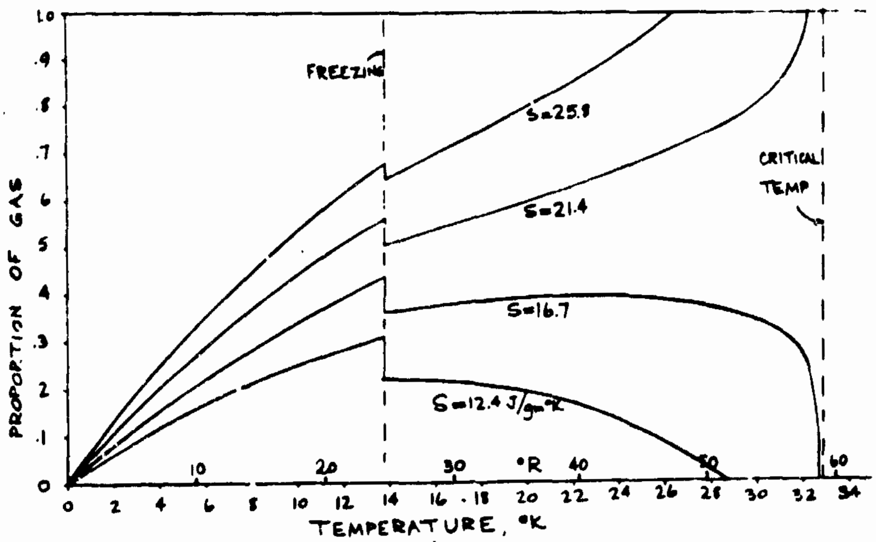


Figure 2-3. Freezing Characteristics of Cryogenic Hydrogen

It is also of interest to note how nonlinearly the pressure decreases with the temperature, as shown by the bottom scale of Figure 2-2.

Typically, the TNT equivalent of cryogenics is relatively low. As a comparison, Table 2-8 compares the TNT equivalent of hydrogen at typical subcritical cryogenic storage conditions as a liquid, with the same temperature and pressure as a gas, and with typical high pressure storage conditions as a gas at room temperature.

Table 2-8. TNT Equivalent of Hydrogen Stored at Typical Cryogenic and High Pressure Gas Conditions

Pressure Atm.	Temperature °K (°R)	Phase	TNT Equivalent kg/kg H_2 (lb/lbH_2)	
			Expanding to 1 Atm.	Expanding to Vacuum
6.8	29 (52)	Liquid	0.006	0.056
6.8	29 (52)	Gas	0.031	0.134
20.4	294 (530)	Gas	0.52	0.75

Blast Overpressure

Face and side on overpressures resulting from an explosion are shown in Figure 2-4 as a function of blast source TNT equivalent and distance from the source.

The maximum allowable cargo bay pressure for a typical orbiter design of 13,800 N/m^2 (2 psi) is shown for reference together with the maximum allowable face-on overpressure, 20,700 N/m^2 (3 psi), permissible for personnel exposure without additional protection.

The figure shows that considerable cargo bay damage could result from an uncontained explosion within the bay with less than 0.0045 kg (0.01 lb) TNT equivalent. For example, if a blast of this energy equivalent were detonated in the center of a 4.6 m (15 ft) diameter by 18.3 m (60 ft) length cargo bay, the structure located at a distance of 2.3 m (7.5 ft) would be exposed to an overpressure in excess of 69,000 N/m^2 (10 psi), while the ends of the bay would be exposed to slightly greater than 6900 N/m^2 (1 psi).

Figure 2-5 shows the TNT equivalent per unit volume of diatomic gases as a function of pressure.

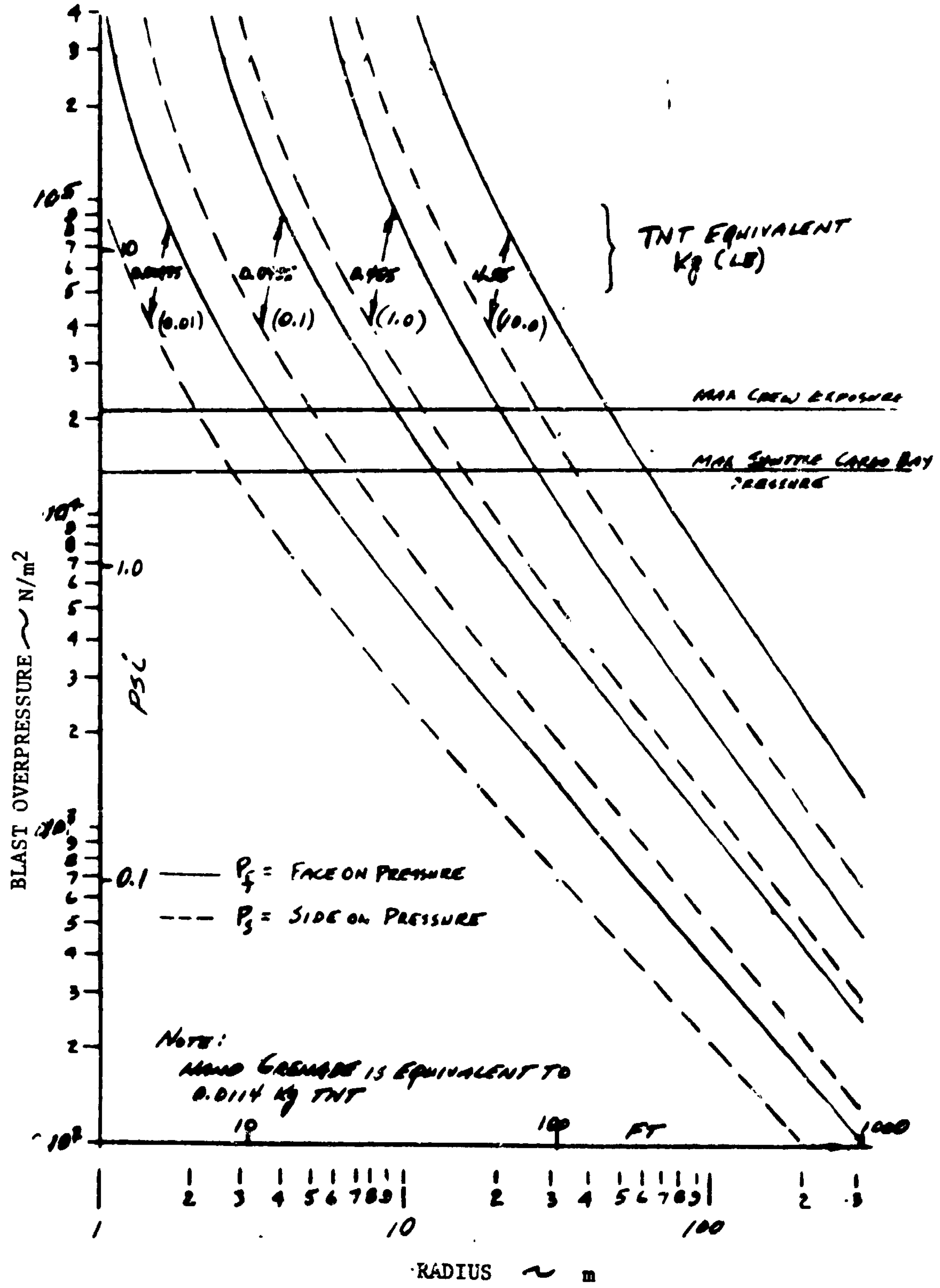
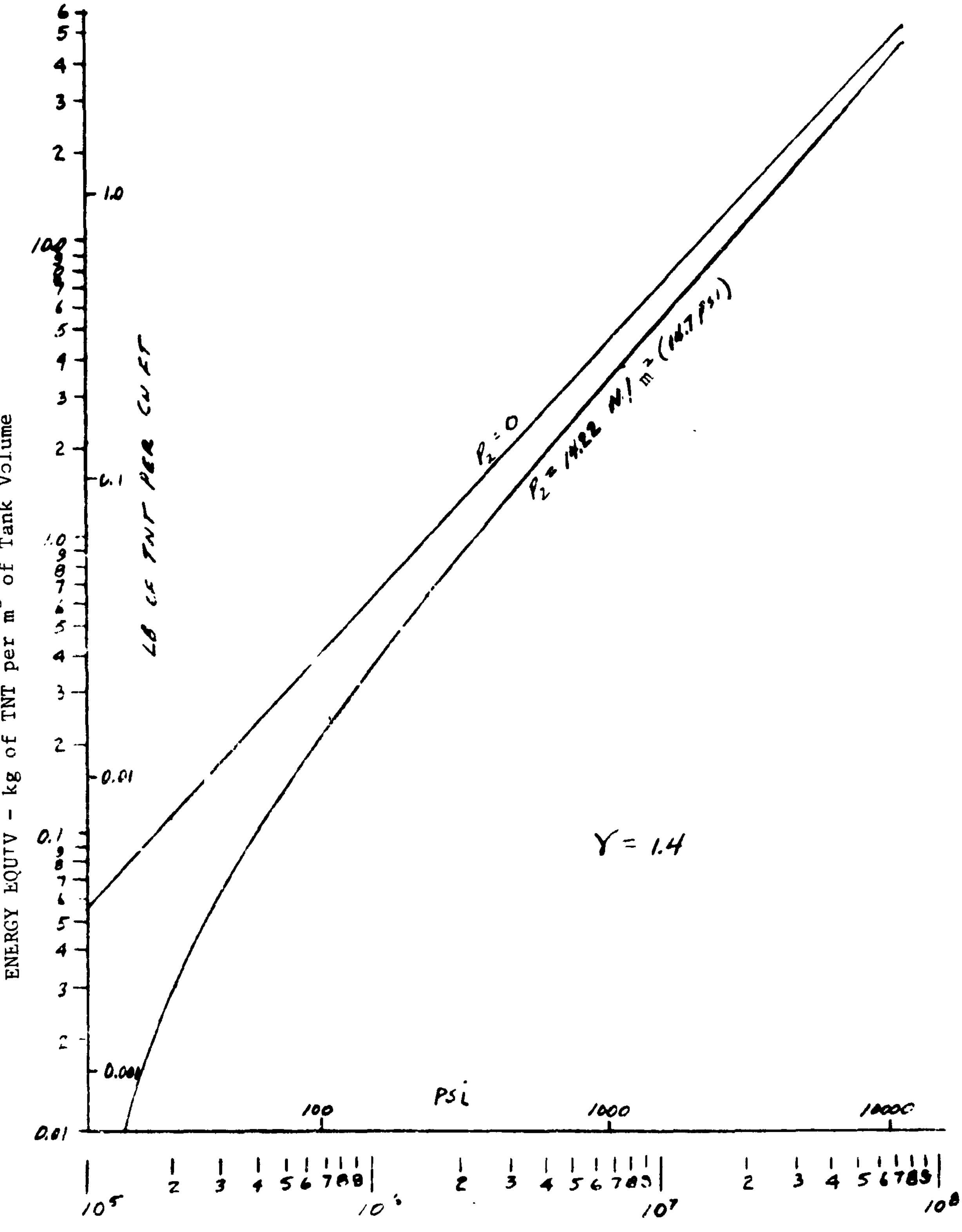


Figure 2-4. Blast Overpressures



TANK PRESSURE ~ kg/cm²

Figure 2-5. Compressed Gas TNT Equivalent for Ideal Gas

Maximum Tolerable Leak Rate into Shuttle Cargo Bay

An investigation was made to determine the maximum allowable leak rate which can be tolerated into the shuttle cargo bay from a pressurized payload vessel. The shuttle cargo bay doors were assumed to be closed and the bay provided with vents to limit cargo bay differential pressures to less than 13,800 N/m^2 (2 psi). A vent area to cargo bay volume ratio of approximately 13.8 cm^2/m^3 (0.06 in^2/ft^3) which has been previously used in NR shuttle venting studies, was assumed to estimate the venting area for any known cargo bay volume.

The maximum tolerable leak rate as a function of vent area is shown in Figure 2-6 and assumes a gas temperature of -205°C (-328°F) (typical temperatures of gases that have leaked into the cargo bay), a maximum allowable cargo bay differential pressure of 13,800 N/m^2 (2 psi), and a discharge coefficient for the vent of 0.85. The leak rate is relatively insensitive to the gas temperature, varying inversely as the square root of the absolute temperature.

It is seen that the maximum leak rate which can be tolerated is larger for gases of high molecular weight than gases of low molecular weight, and that leakage of hydrogen represents the worst case.

Current NR orbiter designs use always-open cargo bay vents of approximately 0.37 m^2 (4 ft^2) area. The maximum tolerable steady state leakage rate into the cargo bay, with doors closed, is of the order of 2.5 kg/sec (5.5 lb/sec) for hydrogen and 20 kg/sec (45 lb/sec) for air, oxygen or nitrogen. Larger leakage rates into the cargo bay can be tolerated for shorter durations, until the cargo bay pressure goes from vacuum to the tolerable limit. Such a large leakage rate for a prolonged period is approaching, in its damaging effects, an explosive rupture of a tank rather than leakage.

It can be concluded that overpressurization of the orbiter cargo bay for normal cargo is not a major hazard. It must be considered, however, for payloads containing mostly propellants, such as upper stage vehicles or propellant logistics resupply. The hazard is then serious, however, only during the time the cargo bay doors remain closed.

Man-Compatibility of Tug while in or Near Orbiter

Upper stage vehicles must be man-compatible; i.e., man rating safety criteria must be applied to systems and functions of the upper stage vehicle which could create a hazard to the orbiter while the upper stage vehicle is in or near the orbiter. The term man-rating, while not strictly defined, means that the safety, i.e., lack of hazards to the shuttle and shuttle personnel, has been adequately demonstrated so that the residual risks to personnel are judged to be acceptable. This is, of course, a subjective matter and no definite man-rating criteria can be cited.

On the Saturn S-II and Apollo CSM programs, two successful unmanned flights were the last phases of man-rating a new launch vehicle. It is not clear what the equivalent requirement is for upper stage vehicles, since the mission phases which require man-compatibility are the relatively passive phases of launch, boost, on-orbit deployment and retrieval, deorbit, reentry, and landing.

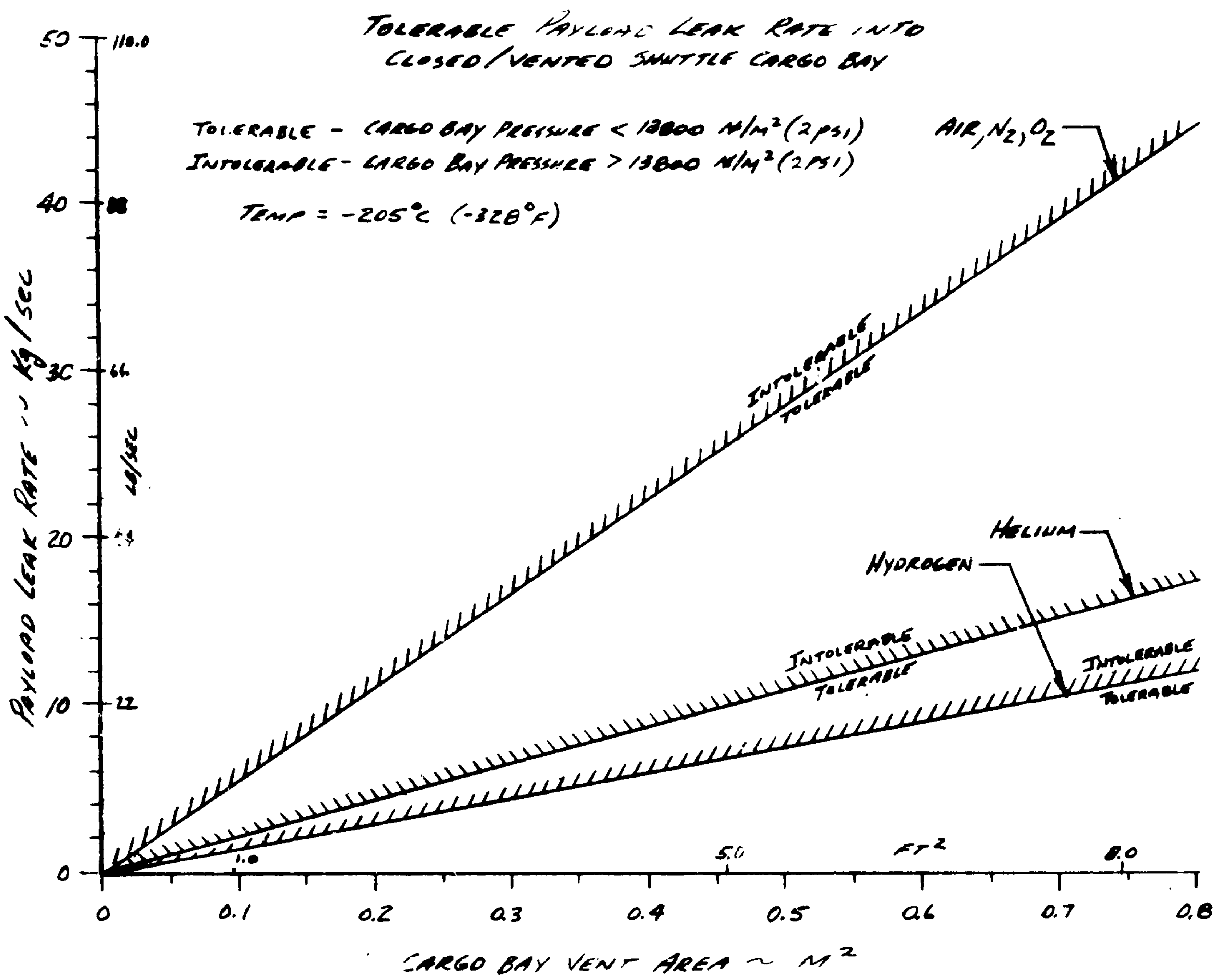


Figure 2-6. Tolerable Payload Leak Rate Into Closed/Vented Shuttle Cargo Bay

The test requirements for man-compatibility must therefore be developed, and must be consistent with the corresponding man-rating requirements on the shuttle.

One possibility is that a safe unmanned test be performed on the shuttle, in which one or both propellants are replaced by equivalent fluids which cannot react chemically. For example, LO_2/LH_2 vehicles may be launched into orbit and returned to earth using LN_2/LH_2. The liquid nitrogen will provide an adequate simulation of the liquid oxygen, but neither the nitrogen nor the hydrogen on their own, nor in combination, can produce a chemical reaction. Other propellants can be replaced by chemically inert fluids with analogous density, thermal, and other properties. Such a flight test can be used to satisfy man-compatibility requirements; but it can also be used as a part of the vehicle qualification testing because the shuttle environment is perfectly reproduced. Such combined testing may prove very cost effective, replacing a large portion of the ground qualification testing, as well as satisfying the man-compatibility requirement.

An alternative man-compatibility test may consist of launching the upper stage vehicle into orbit as a kickstage, using a booster which exhibits environments at least as severe as the shuttle. Such a test imposes design constraints on new upper stage vehicles (i.e., the tug/OOS) to make it compatible with the shuttle orbiter and with the other booster.

3.0 SHUTTLE TO SPACE STATION DOCKING OPTIONS

The Space Station Program Phase B definition studies identified a concern as to the best way to effect docking between the shuttle orbiter and the space station. The safety aspects of bringing these two large and massive vehicles together were a prime consideration in the suggested docking methods.

Among the systems that have been considered for docking are:

- The direct docking of the shuttle orbiter to the space station, as in the Apollo Program.
- The use of manipulators, on either the orbiter or station, to effect a more mechanically determinate docking maneuver, and at a much lower contact velocity than is practical with direct docking.
- An extendable soft-dock system which provides a large distance between the docking vehicles at initial contact, and reduces the docking loads through the flexibility of the system.
- Free-flying and docking the individual space station or other modules between orbiter and station, so as to avoid the close proximity of orbiter and station. The station and the orbiter stationkeep at some distance from each other.

The purpose of this task was to identify, analyze and recommend resolution of the hazards involved in the suggested methods for docking the orbiter to the modular space station; and to make recommendations as to the preferred docking methods from the safety point of view.

Three kinds of operations were considered:

- Assembly of the modular space station
- Normal resupply docking
- Emergency docking

The comparison of the various docking options was divided into two essentially uncoupled tradeoffs. One tradeoff was between three docking systems, and the other between two docking modes. The three docking systems (Fig. 3-1a) are:

- Direct docking system
- Extendable tunnel docking system
- Manipulator docking system

The two docking modes (Fig. 3-2b) are:

- Orbiter to station docking mode
- Free-flying module docking mode

The hazards identified in this task, and the resulting analyses, are applicable to any combination of docking vehicles which use the docking systems and modes considered here, providing at least one of the vehicles is manned. The conclusions and recommendations reached, however, cannot be applied to all such vehicle combinations without careful re-evaluation. The reason is that the effects and criticality of the hazards may differ according to the configuration, size, mass, control systems, and other features of the vehicles. The further these features vary from the orbiter, space station, and individual free-flying modules considered here, the less the confidence that can be placed on the applicability of the results and conclusions.

Further differences which may invalidate the results of this task arise when additional hazards exist because of the nature of the vehicles. For example, when one of the docking vehicles is a propulsion stage (e.g., a tug) or contains large quantities of propellants (e.g., a propellant depot), hazards associated with propellant slosh, leaks, etc., must be additionally considered. Another example is a reusable nuclear shuttle, which poses nuclear radiation hazards. For such vehicles, the conclusions of this task must be re-assessed.

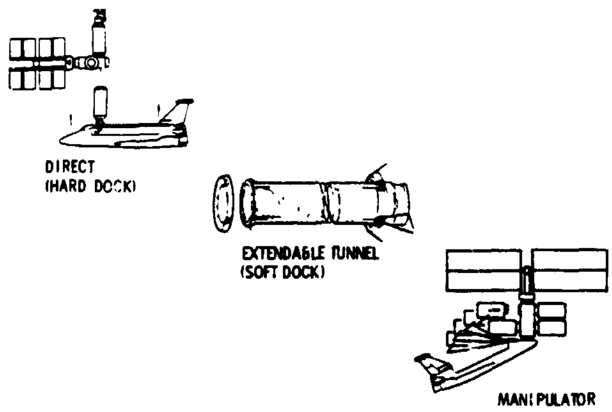


Figure 3-1(a). Docking Svstems

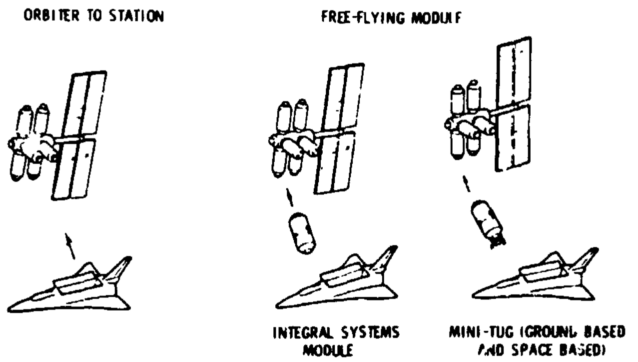


Figure 3-1(b). Docking Modes

3.1 CONCLUSIONS AND RECOMMENDATIONS

The conclusions reached in the evaluation of the docking systems are as follows.

- Each of the three docking systems--direct docking, extendable tunnel and manipulator--can be made adequately safe.
- The stationkeeping and the dual manipulator methods of using the manipulator docking system have the potential of personnel loss in the event of loss of manipulator control before a manned attached module is docked. This remains a residual hazard even when complex emergency life support requirements are added to the manned modules. The dual docking method requires more operations to effect docking, but does not have the potential for loss of personnel.
- All three docking systems have the potential of damage to the docking system and damage to the vehicles. The damage to the spacecraft could, in certain circumstances, be critical enough to result in loss of vehicle or loss of personnel.
- The direct docking system has the greatest potential for inadvertent collision because of the close proximity of the docking vehicles.
- The manipulator docking system has the minimum potential for inadvertent collision between vehicles because of the relatively large separation distance at initial capture, but has more potential failure modes which can result in inadvertent contact and damage.
- The direct docking can perform a time critical emergency docking quicker than the other systems. The manipulator docking system has more potential for docking with an out-of-control, tumbling or spinning spacecraft.
- The hazards and risks of the three systems are not equally well understood because of the different development status of the systems. The direct docking system is relatively well understood from Gemini and Apollo experience; the manipulator system has been defined to some extent in the Shuttle Phase B studies. but has not been tested or simulated at the time of this study; and the extendable tunnel system is only in a conceptual stage.
- The safety advantages and disadvantages of the three systems are sufficiently balanced and uncertainties in the current system definition are such that a ranking of the system from the safety point of view cannot be made at present.
- If the docking systems, when developed, operate as assumed in the study, i.e., without any major additional complications in the design or additional hazards, then the extendable tunnel system appears to require the least attention to make it adequately safe, and the manipulator system the most.

The conclusions reached on the docking modes are summarized as follows:

- The free-flying docking mode has a potential for personnel loss when used to transfer personnel between orbiter and station. The necessary safety requirements for 6 men on the free-flying module reduce the payload capability by 500 kg (1200 lb) and 3 m^3 (100 ft^3), but the potential for personnel loss remains a residual hazard.

- The free-flying module docking mode precludes the possibility of a single accident resulting in loss of both the orbiter and station.

- No significant safety differences exist between the integral systems modules, space-based mini tug, and ground-based mini tug methods of using the free-flying module docking mode.

- The orbiter to station docking mode has more potential of causing major damage to the orbiter and/or station than the free-flying docking mode, but does not directly lead to personnel loss. Loss of personnel or loss of a vehicle as a result of the damage is possible but not likely.

- Use of the free-flying mode for transferring only unmanned modules between orbiter and station eliminates the potential of personnel loss during transfer. It also has a reduced potential for vehicle contact and damage compared to the orbiter to station docking mode because of the simpler geometry and smaller docking energy involved.

- The orbiter to station docking mode provides significantly quicker docking than the free-flying mode in the event of a time critical docking requirement.

The recommendations that result from this task are based on the following precedence of safety selection critiera:

- A system or mode which has the lesser potential for personnel loss is preferred.

- Of the remaining choices, the system or mode in which the safety requirements can result in a significantly lesser risk (in terms of probability and severity of damage) is preferred.

- Where the requirements result in essentially equal risk, the choice in which the requirements and guidelines result in significantly less design impact is preferred.

- The capability to better deal with an emergency situation is considered in the recommendations, but is weighted relatively lightly because there is no clear-cut advantage to any of the systems or modes, and because of the low probability of an emergency docking being required.

These recommendations are:

- The direct docking, extendable tunnel, and manipulator docking systems should all be considered as acceptable docking systems from the safety point of view.
- The stationkeeping and dual manipulator methods of using the manipulator docking system should be rejected as practical options for personnel transfer in normal operations because of their high potential for personnel loss. The methods are acceptable for transfer of unmanned modules or for emergencies.
- The use of the free-flying docking mode for the transfer of manned modules should be rejected for normal operations because of the potential for personnel loss. This mode may be used in emergencies.
- The orbiter-to-station docking mode should be considered acceptable from the safety point of view with any of the acceptable docking systems.
- If mini tugs (such as remote maneuvering units) or modules with self-contained propulsion, control and docking capabilities (such as the space tug) are developed for other purposes and are available, their use in transferring unmanned modules or payloads between orbiter and station should be considered as an acceptable docking mode. Use of this free-flying module mode for unmanned payloads in conjunction with the use of the orbiter to station mode for all manned modules has significant safety advantages.

3.2 RESIDUAL HAZARDS AND HAZARDS RESOLUTION

This section summarizes the hazards identified and their resolution and presents the resulting requirements for supporting research and technology.

3.2.1 Resolution of Identified Hazards

The 23 hazards identified in this task and their disposition is shown in Table 3-1. This shows the judgments of the investigators as to which hazards should be resolved by implementation of the recommended requirements and guidelines; which are residual hazards; which of the residual hazards represent acceptable risks; and which require supporting research and technology (SRT) or must at present be considered as unresolved safety issues.

3.2.2 Supporting Research and Technology Requirements

The supporting research and technology requirements resulting from the areas of uncertainty of this task are listed below. The main originating hazards/emergency are indicated in parenthesis.

Table 3-1. Hazards Resolution

Hazard No.	Hazard	Resolved	Residual	Acceptable Risk	SRT Require-ments	Unresolved Safety Issue
2.1.001	Impairment or visibility at critical moment.	X				
2.1.002	Loss of vehicle control prior to docking contact.		X		X	
2.1.003	Loss of vehicle control after initial contact.		X		X	
2.1.004	Failure to inhibit attitude hold of one vehicle after capture.	X				
2.1.005	Loss of docking system function or control.		X	X		
2.1.006	Failure of orbiter payload module deployment mechanism.		X	X		
2.1.007	Hardware protrusions in the docking tunnel.	X				
2.1.008	Unsecured equipment and personnel during docking.	X				
2.1.009	Degradation of life support system.	X				
2.1.010	Docking hatch opened when pressure equalization incomplete.	X				
2.1.011	Electric discharge during initial contact.	X				
2.2.001	Loss of vehicle control in close proximity to other vehicle.		X		X	
2.2.002	Loss of attenuation capability.	X				

Table 3-1. Hazards Resolution (Cont.)

Hazard No.	Hazard	Resolved	Residual	Acceptable Risk	SRT Require-ments	Unresolved Safety Issue
2.3.001	Loss of vehicle control prior to docking contact by extendable tunnel.		X		X	
2.3.002	Loss of vehicle control after capture by extendable tunnel docking system.		X		X	
2.3.003	Loss of pressure in the pneumatic extension and energy absorption system.	X				
2.4.001	Loss of vehicle control prior to capture by manipulator.		X		X	
2.4.002	Loss of vehicle control after capture by manipulator.		X		X	
2.4.003	Loss of manipulator joint motor control.		X		X	
2.4.004	Loss of manipulator computer aided control system.	X				
2.5.001	Loss of Communications/Command capability during docking by unmanned free flying module.		X	X		
2.5.002	Loss of propulsion or control capability during docking by manned free flying module.		X			X
2.5.003	Loss of life support capability during docking by manned free flying module.		X	X		

- The feasibility using a non-collision approach path during the docking maneuver until the approach velocity is reduced to within the docking attenuation capability should be investigated. Orbital mechanics, guidance, propellants penalties, optical aids and human factors should be considered, and detailed procedures developed. The risks and other factors of this method should be evaluated and compared with the direct (collision path) approach, (Fig. 3-12).

- The dynamics of the docking maneuver under various nominal and worst case conditions should be investigated to assure that design requirements and operational procedures are available under all credible conditions to ensure the safety of the vehicles. Special attention should be given to vehicle conditions with maximum offsets of the docking port from the center of gravity, and to control system or propulsion failures immediately before or after contact.

- Simulation studies of the dynamics and crew capabilities of the manipulator docking system should be conducted at the earliest possible time in order to understand the dynamic characteristics of the system and to identify and resolve hazards which are not apparent from conceptual studies. A safety analysis should be an integral part of such simulations.

3.3 BASELINE MODEL

The baseline model described in this section illustrates the features of the three docking systems, the two docking modes, and the assembly, normal resupply docking and emergency docking operations which were considered during this task.

3.3.1 Direct Docking System

The use of the direct docking system is illustrated in Figure 3-2(a) for the orbiter to station docking. Direct docking may also occur when a free-flying module docks either to a station or to an orbiter. It involves the approach of the two docking vehicles right up to each other so that the integrally attached docking mechanisms can make contact for initial capture. The direct docking system requires the dissipation of relatively large energy levels because of the coarse velocity control expected for propulsive maneuvers of the large masses involved.

3.3.2 Extendable Tunnel Docking System

The extendable tunnel docking system uses an extension mechanism of some kind so as to extend the docking mechanism on one of the two docking vehicles some distance from the vehicle before effecting initial contact and capture, and is then retracted to draw the two vehicles together for rigidizing. The distinguishing features of the extendable tunnel docking system are that it provides a long separation distance of the two vehicles at the instant of first contact, it provides stability after capture and during drawn down, and affords a long storke, low stiffness attenuation capability.

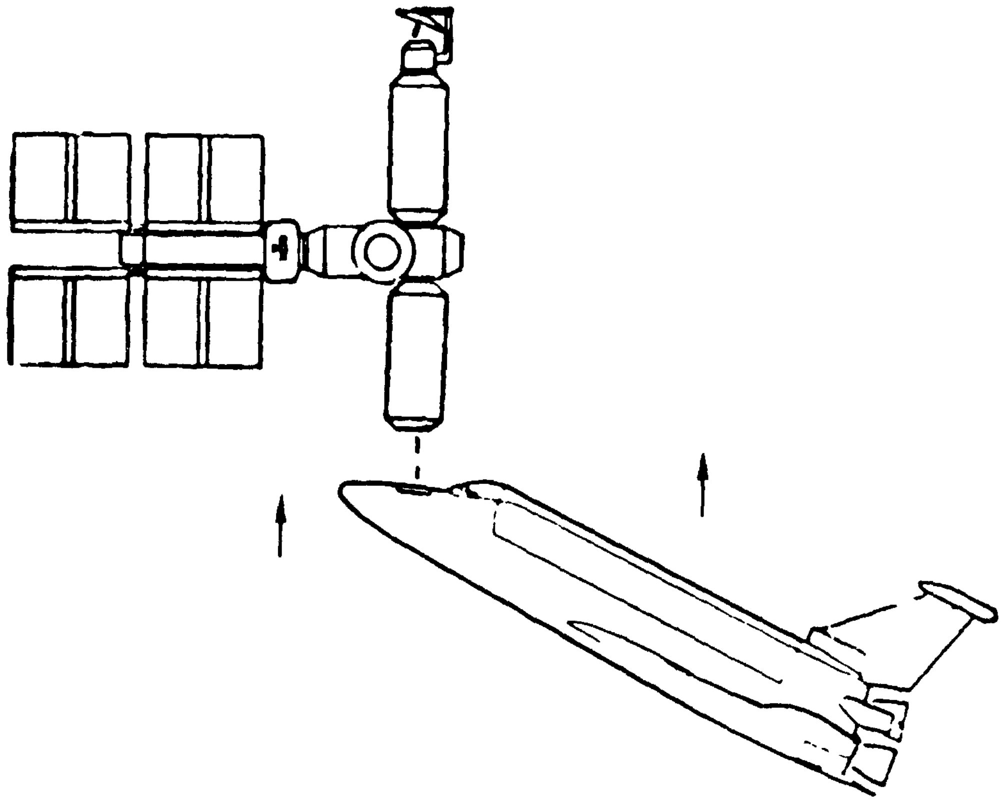


Figure 3-2(a). Direct Docking System Operations

One extendable tunnel docking system concept adapted from a concept considered for the Apollo, is shown in Figure 3-2(b). It employs a docking port attached to one end of an accordian-like bellows tube, extendable to approximately 3 m (10 ft) in length. Tests in two-dimensional simulated docking of the Apollo of this system showed that it was feasible and had no major problems.

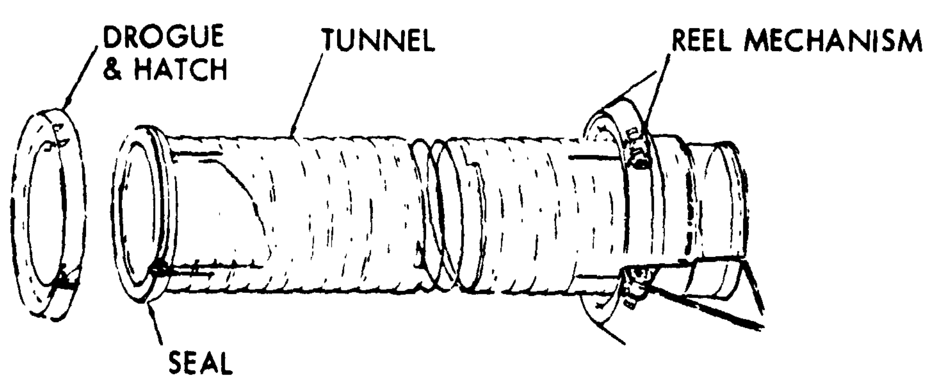


Figure 3-2(b). Extendable Tunnel Docking System Concept

The extendable tunnel system can be used in two different methods. In the first method, illustrated in Figure 3-3, the docking system is first fully extended, and initial contact and capture are effected by propulsive maneuvering of the whole vehicle. In the second method, illustrated in Figure 3-4, the two vehicles stationkeep at a relatively close distance before the docking system is extended, and initial contact and capture are effected by extending the docking system relative to the stationary vehicle. The results of the analyses and the conclusions are applicable, however, whichever method is used.

3.3.3 Manipulator Docking System

The manipulator docking system uses a manipulator on one of the docking vehicles to effect capture of the other one and to bring the two vehicles together for docking, latching and rigidizing. The main features which make the manipulator docking system different from the other systems are that the two docking vehicles stationkeep at some stand-off distance before docking, and that the manipulator brings the two vehicles together at a low controlled velocity. The energy attenuation requirements are low.

Three basic methods can be used for manipulator docking and are illustrated in Figure 3-5. These are respectively:

- Stationkeeping method
- Dual dock method
- Dual manipulator method

All three methods have be considered in the study task.

3.3.4 Orbiter to Station Docking Mode

Two different modes of docking are possible with each of the docking systems describer earlier. These are the orbiter to station docking mode and the free-flying module mode.

The orbiter to station docking mode is illustrated in Figure 3-6. The two vehicles approach each other to within the distance required by the particular docking system used; i.e., within 0.3 to 20 m (1 to 60 ft). This mode results in the attachment through the docking port interface of two large masses, namely the orbiter and station, which are each of the order of 90,000 kg (200,000 lb)

3.3.5 Free-Flying Module Docking Mode

The free-flying module docking mode, illustrated in Figure 3-7, uses a free-flying module to fly between and dock to the orbiter and station. In this way the orbiter and station can stand off from each other in station-keeping modes at a relatively large distance, which may in practice be 150 m to 1.5 km (500 ft to 1 mi). The free-flying module may be manned or unmanned. All dockings occur between an individual module, typically of 9,000 kg (20,000 lb) mass, and the station or orbiter. Docking impact energies are, therefore, only 20 percent or so of those involved in the orbiter to station docking mode (at the same velocity).

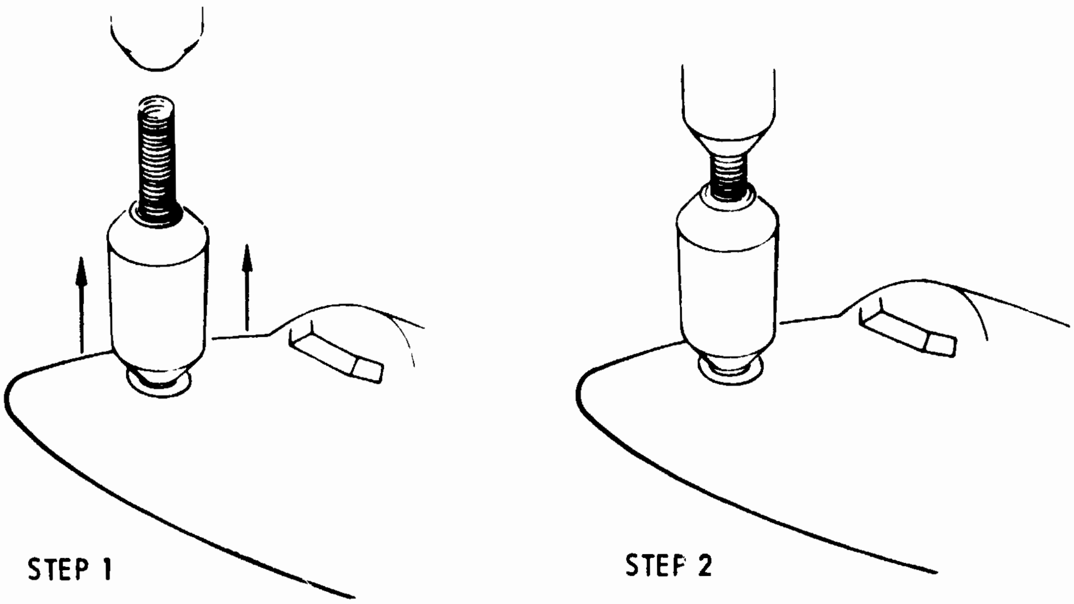


Figure 3-3. Extendable Tunnel Docking System, Docking Vehicle Active

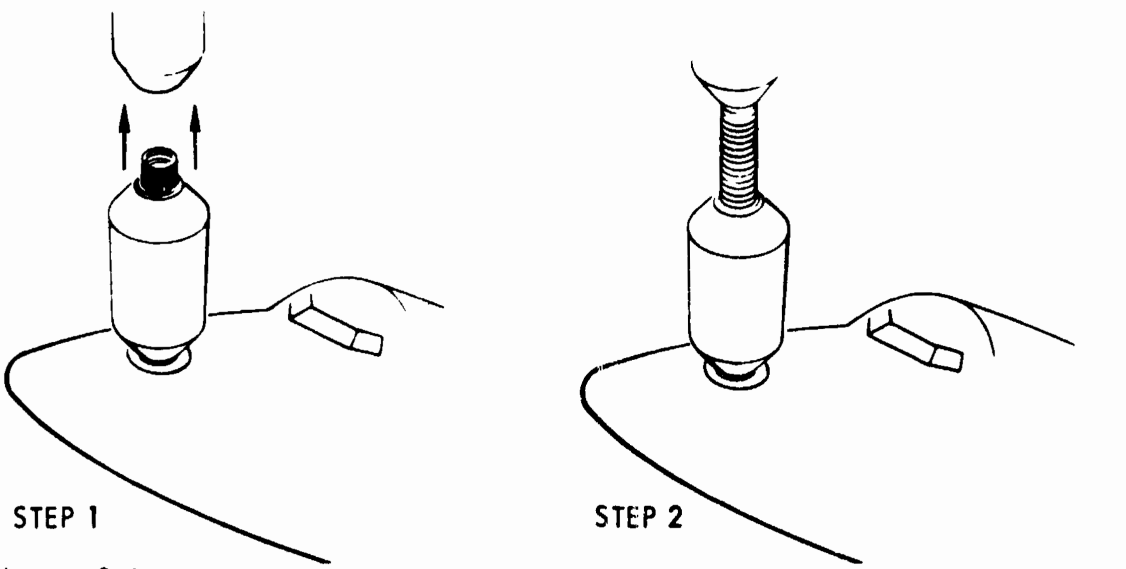
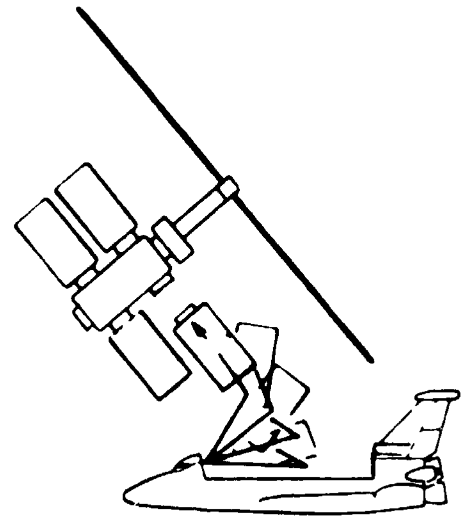
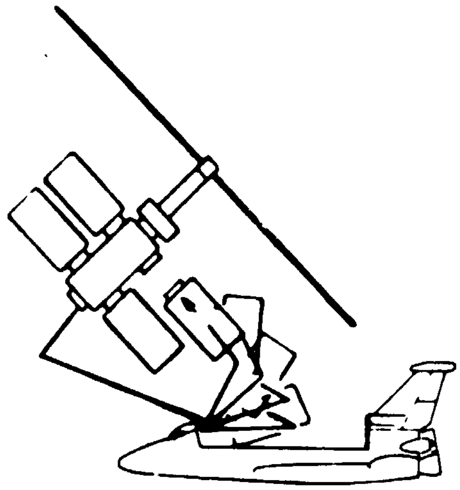


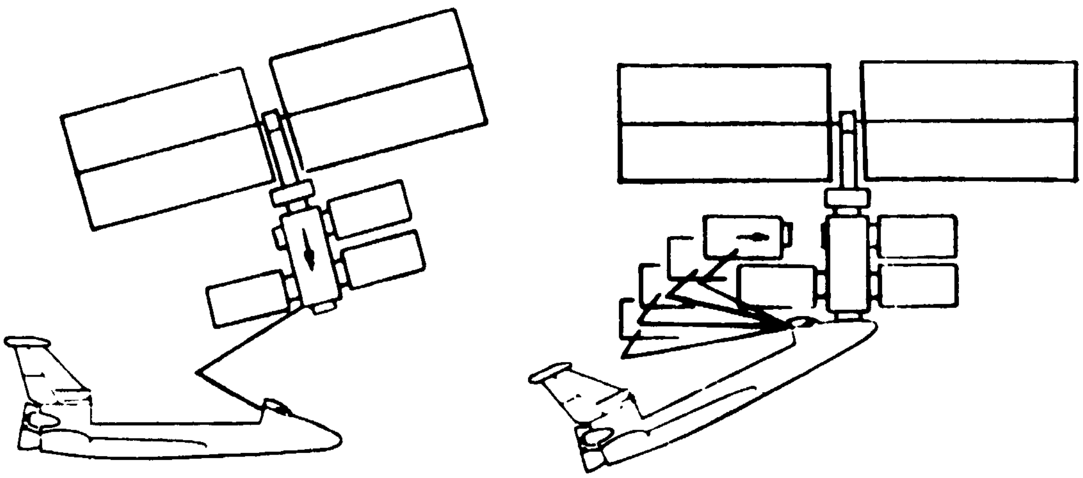
Figure 3-4. Extendable Tunnel Docking System - Docking Vehicle Station-Keeping, Docking System Active



STATIONKEEPING DOCKING METHOD



DUAL MANIPULATOR DOCKING METHOD



DUAL DOCK DOCKING METHOD

Figure 3-5. Stationkeeping, Dual Manipulator and Dual Dock Methods

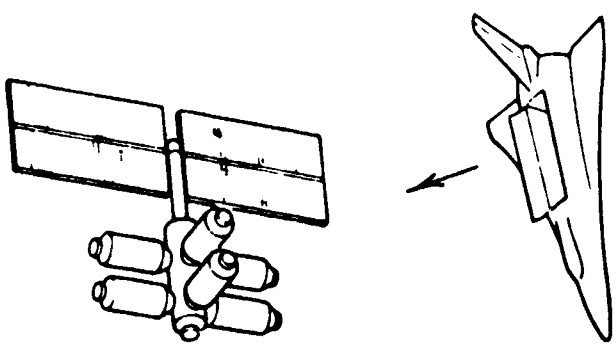


Figure 3-6. Orbiter to Station Docking Mode

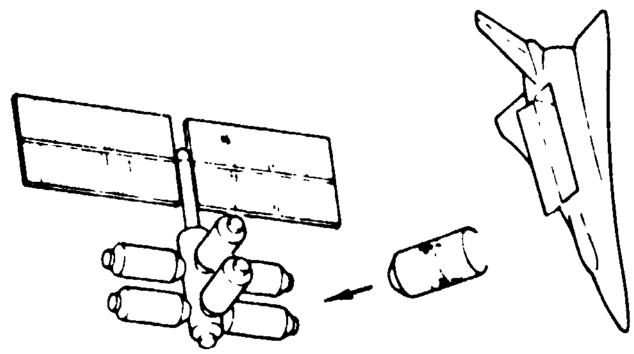


Figure 3-7. Free-Flying Module Docking Mode

Attitude control, propulsion, guidance and communications capability may be achieved in three distinct ways:

- Integral systems module, i.e., all functions are built into the free-flying module
- Space-based mini tug, i.e., brought up in the orbiter
- Ground-based mini tug, i.e., normally based on the space station

3.3.6 Emergency Docking

Analysis of the docking system included consideration of emergency docking to identify hazards and considerations in tradeoff evaluations.

Identification and evaluation of potential emergencies has shown that, so far as docking is concerned, emergency docking is characterized by one of the following two situations:

1. A time critical situation on the orbiter, free-flying module, or station, in which a docking is required to save or prevent injury to personnel or damage to the vehicles, or otherwise prevent a hazardous or dangerous situation from reaching catastrophic proportions.

   Examples of time critical situations are fire, fumes, impending explosion, leakage, atmospheric depressurization, failure of life support, power failure, and injured personnel.

2. Docking to a vehicle which has lost or experienced degradation of a critical docking function.

   Examples are attitude control failure and uncontrolled tumbling.

Both of these emergency docking operations have been considered in the subsequent analyses.

3.4 HAZARDS IDENTIFICATION

Potential hazards associated with the docking systems and modes were identified by setting out the functions which have to be performed, and then considering what hazards may arise in each function from equipment failures, operational errors, unexpected environments and major malfunctions or accidents.

3.4.1 Functional Analysis of Docking Systems

Top-level functions required for docking of two spacecraft are listed in Table 3-2. These are general, and are applicable to any set of vehicles, and to all the docking systems and docking modes considered.

Table 3-2. Top-Level Functions Required for Docking

Pre-Contact Flight Phase

1. Acquisition - One vehicle must locate the other either visually or electronically.

2. Gross Orientation - One vehicle must maintain attitude hold, while the other translates and rotates into alignment. The vehicle maintaining attitude hold will be called the "passive" vehicle.

3. Station Keeping - The active vehicle must station keep with the passive vehicle for inspection of the docking port condition. Active vehicle attitude hold is required.

4. Deploy Docking System - The active vehicle must deploy or arm the active portion of the docking system.

5. Fine Orientation - The active vehicle must fine align the active docking system with respect to the passive vehicle docking port in both translation and rotation.

6. Final Closure - The active vehicle docking interface must be maneuvered to contact the passive vehicle docking port. Lateral drift and residual attitude misalignment must be corrected during axial closure.

Contact Phase

1. Energy Attenuation - The active vehicle docking system must absorb the energy of relative motion between the two vehicles.

Post-Contact Phase

1. Capture - The active vehicle mating system must provide connection to the passive vehicle.

2. Attitude Alignment - Residual attitude misalignments between the vehicles must be corrected either by active vehicle maneuvering or by the capture mechanism prior to seating the mating interfaces. If the capture mechanism provides attitude alignment, the active vehicle must be placed in the free mode (i.e., no attitude hold). The passive vehicle remains in the attitude hold mode. Failure to inhibit attitude hold on one of the vehicles will cause both control systems to fight to hold their respective misaligned attitudes.

Table 3-2. Top-Level Functions Required for Docking (Cont.)

Post-Contact Phase (Continued)

3. Draw Down - The docking interfaces must be drawn together to remove residual attenuation stroke and seat the interfaces.

4. Rigidizing - The docking interfaces must be structurally connected either automatically or manually to provide the required inter-vehicular stiffness for combined vehicle maneuvering. This function also can seat pressure seals if intervehicular press-urization is required.

Undocking Phase

1. Unrigidize - The docking interfaces must be structurally dis-connected to provide a flexible coupling for independent vehicle maneuvering. This function can also unseat pressure seals and be combined with the separation function.

2. Separate - The docking interfaces must be physically separated. Energy stored in the docking system may be used to provide or augment separation forces.

3. Recycle Docking System - The docking interface must be left in a condition to dock again. The rigidizing latches shall extend the attenuators to the unstroked position, the capture latches shall be unlocked and recycled, and the docking systems stored.

Table 3-4. Comparison of Operations for Manipulator Docking Methods

Operation	METHOD		
	Station Keeping	Dual Dock	Dual Manipulator (1)= Manip #1 (2)= Manip #2
o Attach manipulator to module in cargo bay	X		
o Extend manipulator	X	X	X(1)
o Attach manipulator to station		X	X(1)
o Attach manipulator to module in cargo bay			X(2)
o Extend manipulator			X(2)
o Dock module to station	X		X(2)
o Release manipulator from module	X		X(2)
o Retract manipulator	X	X	X(2)
o Dock station to orbiter		X	
o Release manipulator from station		X	X(1)
o Attach manipulator to module in cargo bay		X	
o Extended manipulator		X	
o Dock module to station		X	
o Release manipulator from module		X	
o Attach manipulator to station		X	
o Undock station from orbiter		X	
o Extend manipulator		X	
o Release manipulator from station		X	
o Retract manipulator		X	X(1)

Table 3-5. Functional Comparison of Orbiter to Station and Free-Flying Module Docking Modes

Function	MODE: Orbiter to Station (Direct Dock)	Free-Fly Module: Integral Systems Module	Free-Fly Module: Space Based Mini-Tug	Free-Fly Module: Ground Based Mini-Tug
o Undock from station			X	
o Free-fly to orbiter			X	
o Dock to delivered payload module			X	
o Undock delivered payload module from orbiter		X	X	X
o Free-fly (or fly) to station	X	X	X	X
o Dock delivered payload module to station	X	X	X	X
o Undock from delivered payload module	X		Y	X
o Free-fly (transpose) to earth-bound module	Y		Y	Y
o Dock to earthbound module	Y		Y	Y
o Undock earthbound module from station	Y	Y	Y	Y
o Free-fly to orbiter		Y	Y	X & Y
o Dock to orbiter		Y	Y	[illegible] & Y
o Undock from earthbound module			Y	
o Free-fly to station			Y	
o Dock to station			Y	

X = Deliver and dock a module.
Y = Undock and return a module.

Table 3-6. Correlation of Common Hazards with Docking Functions

Docking Function	Hazard										
	Impairment of Visibility	Loss of Vehicle Control Precontact	Loss of Vehicle Control Post Contact	Failure to Inhibit One Vehicle att. Hold	Loss of Docking System Function	Failure of Deployment Mechanism	Hardware Protrusions in Tunnel	Unsecured Equipment During Docking	Degradation of Life Support System	Pressure Not Equalized	Electric Discharge
Pre-contact Flight Phase:											
Acquisition	X	X							X		
Gross Orientation	X	X						X	X		
Stationkeep.	X	X							X		
Deploy dock. sys.	X	X			X	X			X		
Fine orient.	X	X						X	X		
Final Clos.	X	X			X	X		X	X		
Contact Phase: Energy Atten.			X		X			X	X		X
Post Contact Phase:											
Capture			X	X	X			X	X		X
Attitude Align.			X	X	X			X	X		
Draw down			X	X	X			X	X		
Rigidizing			X	X	X		X	X		X	
			X	X	X		X	X			
Undocking Phase											
Unrigidizing			X	X	X		X			X	X
Separation			X		X		X	X		X	X
Recycle Sys.			X			X					

3.5 COMPARISON AND EVALUATION OF DOCKING SYSTEMS

Comparisons of the docking systems were made on the following factors:

- Number of hazards
- Criticality of hazards
- Risk, or combination of probability and criticality
- Operational complexity
- Design impact of applying the safety requirements and guidelines
- Residual hazards

Comparisons on the first three factors is summarized in Figure 3-8. The manipulator system has the worst combination of number of hazards, criticalities and probabilities of occurrence, with the stationkeeping and dual manipulator methods having two hazards with the worst possible combination of criticality and probability.

The next comparison is on the basis of operational complexity. The system with the most operations is exposed to the greatest risk. The significant operations were taken to be the free-fly maneuver, the attachment and detachment of a manipulator to a module, and the docking and undocking of a module, including rigidizing at a docking port. The comparison is shown in Table 3-7. This table covers the normal resupply docking, when a new module is being delivered to the station and another one is returned to the orbiter for return to earth.

The three methods for the manipulator docking systems are shown separately, since they differ in the number of operations. There is also a possible variation, as shown by the asterisked numbers, according to whether the returned module can be reached by the orbiter manipulator without repositioning from its delivery position, or whether the orbiter must reposition itself by a free-flying maneuver to reach the returned module.

No clear-cut statment can be made that one system requires more operations than another.

In order to compare the docking systems on the basis of design impact of applying the safety requirements and guidelines, only those safety requirements and guidelines which are specific to one or other of the systems and which have a significant impact on the design need be considered. Significant design impact is considered to mean the addition of mechanisms, motors, actuators, and similar levels of hardware, for safety reasons.

The following have significant design impact:

<u>Extendable Tunnel</u>

- Extendable docking systems shall be designed so that the extension mechanisms shall retain sufficient rigidity following any single failure to prevent uncontrolled vehicle motion or contact.

SYSTEM	HAZARD	COMPARISON					
		PROBABILITY			CRITICALITY		
		LOW	MEDIUM	HIGH	DOCK SYS. DAMAGE	VEHICLE DAMAGE	PERS. LOSS
DIRECT	LOSS OF CONTROL IN CLOSE PROXIMITY TO OTHER VEHICLE		X			X	
	LOSS OF ATTENUATION CAPABILITY	X				X	
EXTENDABLE	LOSS OF CONTROL PRIOR TO DOCKING CONTACT		X		X		
	LOSS OF CONTROL AFTER CAPTURE		X		X		
	LOSS OF PRESSURE IN TUNNEL		X			X	
MANIPULATOR	LOSS OF CONTROL PRIOR TO CAPTURE BY MANIPULATOR		X			X	
	LOSS OF CONTROL AFTER CAPTURE BY MANIPULATOR		X			X	
	LOSS OF MANIPULATOR JOINT MOTOR CONTROL			X		X(1)	X(2)
	LOSS OF MANIPULATOR COMPUTER AIDED CONTROL			X		X(1)	X(2)

(1) Dual dock docking method
(2) Stationkeeping and dual manipulator docking methods

Figure 3-8. Probability and Criticality of Docking System Hazards

Table 3-7. Number of Operations for Different Docking Systems

System	Operation		
	Free-fly	Attach/Detach	Dock/Undock
Direct Docking	2	-	2
Extendable Tunnel	2	-	2
Manipulator			
Station-keeping	1-2*	2	1
Dual dock	1-2*	3-4*	2-3*
Dual manipulator	1-2*	3-4*	1

*The higher number applies when the orbiter must be repositioned to reach the module being returned.

Manipulators

- Arm joints shall be designed to lock on indication of joint motor failure. Lock shall incorporate a slip clutch capability to prevent structural failures.

- Two or more manipulators shall be provided in a manipulator docking system. Each manipulator shall be capable of performing docking by itself, and shall also be capable of continuing any docking function in the event of a failure of the other manipulator at any stage of the docking.

- An emergency jettisioning capability shall be provided for manipulators, independent of the normal manipulator system. This shall be capable of jettisoning the manipulator following a failure or accident which does not allow stowage of the manipulator and configuring the orbiter for reentry and landing.

If the manipulator docking system is considered for transferring personnel between orbiter and station using the stationkeeping or the dual manipulator methods, the following two additional requirements have a major design impact.

- Modules which are used for personnel transfer by manipulator docking shall be provided with EVA pressure suits for all onboard personnel, and with EVA exit capability so that the personnel can escape to the orbiter or the space station in the event the module becomes stranded between vehicles by a manipulator failure.

- Modules which are used for personnel transfer by manipulator docking shall be provided with EVA pressure suits for all onboard personnel, and with EVA exit capability so that the personnel can escape to the orbiter or the space station in the event the modules becomes stranded between vehicles by a manipulator failure.

- Modules which are used for personnel transfer by manipulator docking shall provide emergency life support for all onboard personnel, until they can escape or be rescued by external means in the event the module becomes stranded between vehicles by a manipulator failure.

The last comparison is in terms of residual hazards. The comparison shows:

- Direct docking system - 2 residual hazards
- Extendable tunnel system - 3 residual hazards
- Manipulator docking system - 4 residual hazards

3.6 COMPARISON AND EVALUATION OF DOCKING MODES

The orbiter to station and free-flying module modes were compared on the following factors:

- The potential for crew injury or loss
- The potential for vehicle loss
- The potential for vehicle damage
- The cost and payload impact of required safety

3.6.1 Orbiter to Station Docking Mode

The hazards identified for the orbiter to station docking mode have the potential of causing major damage to the orbiter and/or the station, but do not directly lead to personnel injury or loss. The damage would result from inadvertent contact of parts of the structure not intended to make contact. Because both vehicles are large and have complex geometries, with many protuberances, such as cargo bay doors, wings and manipulators on the orbiter, and solar panels, antennas and experiments airlocks on the station, almost any unprogrammed motion can lead to contact and damage.

Generally the effects would be limited to damage to the vehicle, and the potential for personnel injury or loss should be assessed as a second order effect. The proximity of the orbiter and station, either of which can provide for the long-term safety of personnel (one by return to earth and the other by virtue of its inherent long-duration capability), and the assumed EVA capability virtually ensure that personnel who survive the immediate accident can be safeguarded.

The possibility of loss of one vehicle following a docking accident is quite real, however. The orbiter is vulnerable in a number of ways. The cargo bay doors must be closed before reentry; damage to the closing mechanism, or to

the doors themselves, could result in the ingestion of hot reentry gases, leading to thermal degradation of the internal structure. The wings, fuselage and tail surfaces are part of the aerodynamic configuration, and damage can affect the stability and control of the vehicle in the atmosphere. The crew cabin also is near the docking port, and damage to that could preclude return to earth. If an assessment of the damage prevents return to earth, a very complex and costly rescue and repair shuttle mission would be required, probably with much EVA maintenance. In extreme cases the orbiter would be written off as a complete loss, and the rescue mission would concentrate on saving the personnel and placing the orbiter on a safe reentry orbit.

The space station, being modular in nature, is much more tolerant to damage. Damage would generally be confined to one module, and this could be returned to earth in the orbiter for repair or replacement. This could be quite difficult, however, if the affected module were the core module, since all other modules are attached to it. In such a case the space station may be temporarily abandoned, and a new core module brought up in due course. The space station would then be reassembled about this module, and the damaged core module returned to earth. Damage to the solar arrays (relatively likely because of the large area exposed) could similarly lead to temporary station abandonment.

3.6.2 Free-Flying Module Docking Mode

The free-flying module docking mode has a very definite potential for personnel loss. If loss of the propulsion, control or life support capability occurs while the module is free flying between orbiter and station with personnel onboard, personnel loss can occur. Escape can only be effected by EVA to the orbiter and station. Rescue is possible by the orbiter, but only if the module can still be stabilized (for docking) and if adequate life support capability remains. The possibility of personnel loss must, therefore, be rated as relatively high. In contrast to the orbiter to station docking mode, loss of personnel can follow directly as a consequence of a system failure, and does not depend on a propagation of unlikely effects. The potential for personnel loss appears to be about the same for the integral systems module, space-based mini tug or ground-based mini tug.

The possibility of an inadvertent collision between the free-flying module and the orbiter or space station is about as likely as for the orbiter to station docking mode. The resultant damage, however, is likely to be much less, for two reasons. First, the geometry of a single module docking to orbiter or station is much simpler, so that fewer points on the two vehicles will come into contact. Secondly, the mass of a free-flying module is only about 10 to 20 percent of the mass of either orbiter or station, so that the energy involved in the collision is relatively small.

The influence of safety on the design complexity of the free-flying module docking mode must be judged to be a major impact. The requirement for a life support system on the module is not considered as a safety requirement, as it is needed for the normal vehicle function of transporting personnel. The redundancy required in this system, the added redundancy in the control, power, propulsion and communication systems, the EVA suits and EVA capability, and the emergency life support capabilities, however, are directly attributable to safety.

These requirements reduce the net payload capability of each 6-man free-flying module by 534 kg (1180 lb) and available for cargo by 3 m^3 (106 ft^3).

3.6.3 Free-Flying Module Docking Mode Used For Unmanned Operations Only

A considerably different safety evaluation of the free-flying module docking mode arises if this mode is used only for transferring unmanned payloads, and the orbiter to station mode is used when personnel transfer between the vehicles is involved. This combined mode could be practical if a mini tug has been developed for other purposes and is available for docking unmanned payloads, or if some orbiter payloads, such as a space tug, have the propulsion and control capability built into them, and require transfer from the orbiter to the station and vice versa.

The advantages compared to the orbiter to station docking mode are those of docking a smaller mass to the orbiter or station, and of the simpler geometry reducing the potential for damage on collision without the disadvantages of a relatively high potential of personnel loss.

This mixed mode, therefore, provides safety advantages over the orbiter to station docking mode on its own, and over the free-flying module docking mode on its own. These advantages apply so long as the free-flying module is not used at all for personnel transfer.

The disadvantages of this mixed mode are not safety disadvantages, but are associated with the program complexity of having two docking modes in the program.

3.7 EMERGENCY DOCKING CONSIDERATIONS

The reasons for emegency docking, establish certain requirements that will determine which of the three docking concepts should be favored from an emergency docking standpoint. The reasons for emergency docking that appear to cover the majority of possibilities are as follows:

- A time critical malfunction of a system in either manned/passive or manned/active vehicles, that if docked to the other, would provide succor or permit mission continuance.
- Retrieval of a disabled, unmanned, free-flying, module or disabled unmanned station for the purpose of salvage or deorbit of debris.
- Time critical transfer of disabled crew which could prevent fatality.
- Time critical transfer of supplies which would prevent crew disability.

Emergency docking considerations favor the orbiter to station docking mode over the free-flying module mode because of its quicker time response. Although the direct docking system is the quickest system, the manipulator system has advantages in increased separation between the vehicles and in capability to deal with out-of-control vehicles

The time critical emergency docking reasons (3 out of 4) favor the docking system and mode requiring the shortest, operational timeline for the docking maneuver; i.e., the fewest docking operations. This favors the orbiter to station docking mode over the free flying module mode, and the direct docking system over the extendable tunnel and manipulator docking systems. The free-flying module mode, in particular, considerably extends the total time from initiation of the docking maneuver to its completion.

However, the importance of reducing the docking time in evaluating the merits of the various docking systems and modes must be kept in perspective. The probability that an emergency occurs when the orbiter and station can initiate a docking maneuver immediately is very remote. If the emergency occurs in the space station, the chances are that no orbiter is in space at the time. A shuttle rescue mission may typically take ten hours from an alert to rendezvous. The difference between one method of docking and another may be 15 minutes (in an emergency mode), and this time is unlikely to be critical to the success of the rescue.

When considering the two docking modes, the time advantage is clearly in the orbiter to station docking mode. In this case the added time for deploying and free flying a module to the distressed vehicle could be up to a few hours, particularly if a mini tug is involved, and this could be a significant addition to the total time available.

The two emergency docking situations that involve spacecraft systems malfunctions could be too hazardous for an approach with a direct docking system. Of the three docking systems considered, only the manipulator has the capability to add its dexterity to that of the active vehicle in the task of capturing a malfunctioning target vehicle. If the emergency consists of the passive vehicle having lost attitude hold capability and it is either tumbling very slowly, within the design capability of the docking system, or is subject to unpredictable motions due to venting, the direct docking system would be the least desirable, because of the close approach of the two vehicles. The manipulator system would offer the best and safest method with the extendable tunnel an intermediate choice.

3.8 DOCKING DYNAMICS WITH DOCKING PORTS OFFSET FROM THE CENTER OF MASS

The current experience of docking on the Gemini and Apollo programs has dealt with the situation in which the centerlines of the docking ports were essentially aligned with the centers of mass of the two docking vehicles. This results in minimum angular motions upon contact.

The current configurations of the orbiter and the modular space station result in docking port alignments which are offset from the respective center of mass as shown in Figure 3-9. This leads to an angular motion of the two vehicles relative to each other upon initial docking contact, which must be cancelled out by the attitude control systems of the vehicles (or by the manipulator, where used for the final docking). The direction of the angular motions (assuming zero angular rates before contact) will be in the same direction for the two vehicles if the docking port lies between the two centers of mass (see Figure 3-10A), or in opposite directions if both centers of mass are on

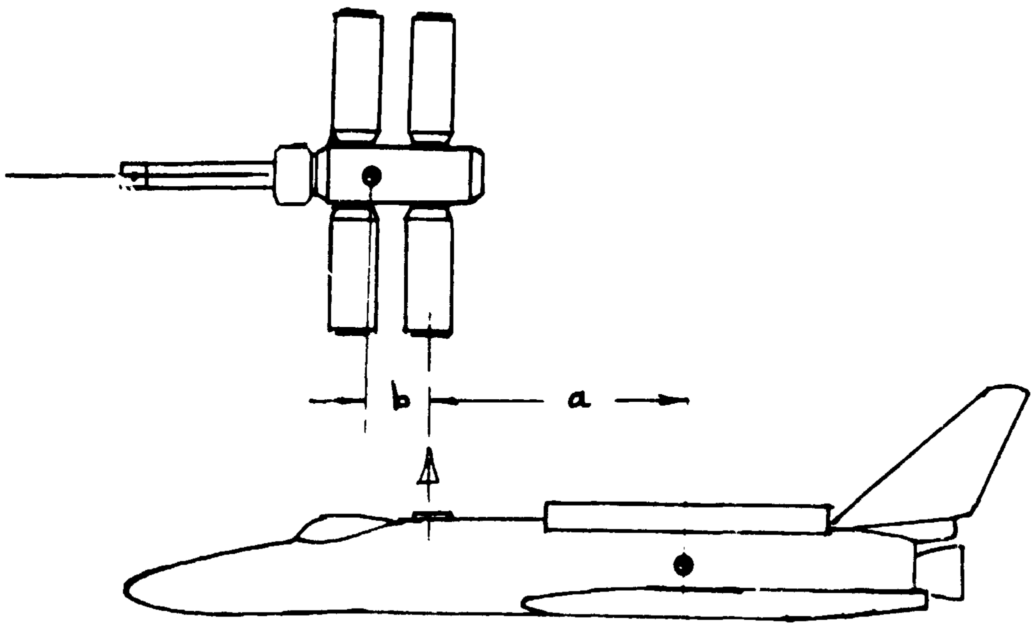


Figure 3-9. Typical Orbiter to Station Docking Configurations Showing Relative Positions of Centers of Mass and Docking Ports.

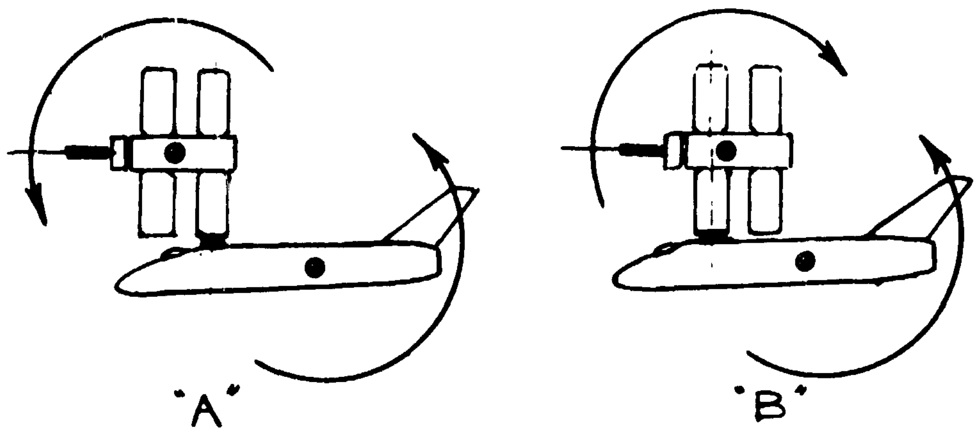


Figure 3-10. Direction of Initial Angular Motions Following Docking.

the same side of the center of mass (see Figure 3-10B). The angular velocity of each vehicle depends on the contact velocity, the vehicle mass, moments of inertia and distance of the center of mass from the docking port. The velocities for the two vehicles will in general be different and if the necessary corrections are not promptly applied by the attitude control systems, contact with the two vehicles with consequent damage will result. The dynamics of the situation, and the consequences of a control system failure at the critical moment are, therefore, of interest from the safety point of view.

The angular excursion which will be experienced depends on the initial angular velocity and the control authority available from the vehicle attitude control system.

The worst situation occurs when a large orbiter docks to a large station. This obviously poses geometric problems, both in the detail design of the docking mechanism itself to allow for such angular misalignments, and in the potential of inadvertent contact between the vehicles.

This sensitivity to docking velocity and control moments is shown in Figure 3-11. This chart shows that for a docking velocity of 0.3 m/sec (1 ft/sec) the station will turn through a 32-degree angle. The station would require 72 seconds to arrest this motion.

Analysis has shown that the orbiter, with control authority about two orders of magnitude greater than that of the station, can counteract angular motions practically simultaneously, and does not have this kind of problem.

A serious hazard occurs if the attitude control system fails after capture, but before motion has been arrested and the vehicles stabilized. If this happens, the attached vehicle will continue its angular motion, the docking interface will be broken, and the vehicles will collide with each other.

The recommended solution is to fly the orbiter so that it follows the space station motion. This would involve complex sensing devices or procedures, to track the station angular motions, and possible minimum impulse attitude adjustments on the orbiter. This maneuvering would continue until the angular motions of the two vehicles have been damped out enough to enable rigidizing to be performed while the two vehicles are still rotating in inertial space.

If the manipulators are used for docking, then the same problem can arise, and the same corrective procedures applied, if the control system failure is in the control system of the manipulator. In this case, however, the motion is much less than for direct docking because of the dynamics (as shown above), the manipulators could possibly provide some damping torques, and the station attitude control system provides a back-up to the manipulator control system. This problem is, therefore, not very severe where manipulators are used for docking.

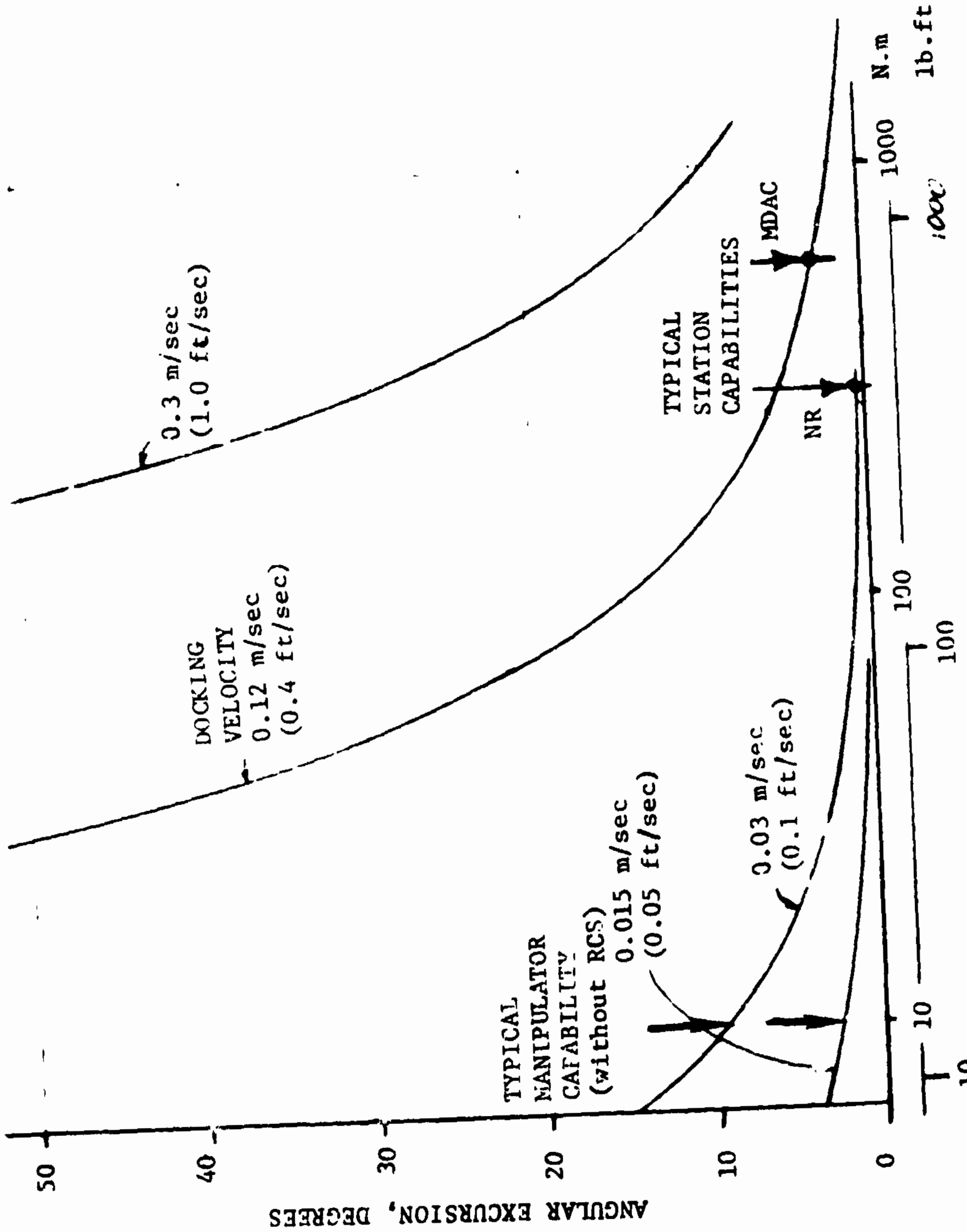


Figure 3-11. Angular Excursion of Typical Space Station Following Initial Docking Capture.

3.9 NON-COLLISION DOCKING APPROACH VECTOR

A potential hazard exists when two docking vehicles approach each other on a line-of-site course, as usually planned for the final docking maneuver. This is essentially a collision course, and if a control system failure occurs on the active vehicle, so that the final velocity reductions cannot be achieved, a collision will occur at a velocity higher than the capability of the docking system with consequent damage.

In order to avoid this hazard, a new procedure is suggested here, which avoids the possibility of an inadvertent collision at too high a velocity. This consists of aiming the approach velocity vector not at the docking port of the target vehicle, but at an imaginary "pseudo-target" some distance to one side of the target vehicle. This is illustrated by Figure 3-12. The pseudo target is sufficiently to the side of the target vehicle that if a control system failure should occur, the active vehicle passes by the target without the possibility of contact. Some margin may be allowed for possible rotations and errors.

This non-collision approach vector is maintained while the velocity of the active vehicle is above the docking system attenuation capability. Deceleration through the various "braking gates" occurs along this direction. The velocity vector is only changed to be on a line-of-site, or collision, course when its velocity has been reduced to within the docking system attenuation capability. If a control system failure occurs now, the docking system can withstand the collision without damage.

Two potential difficulties can be foreseen with this procedure. First, the guidance of the vehicle towards a non-existent pseudo target is a more complex maneuver than a simple line-of-sight approach. It may be found, however, that a "bias" can be introduced simply and reliably into the optical system. The angle of view of the target vehicle will continually change, however.

Secondly, the attitude control system programming is more complex, possibly requiring more propellants, and more complex computer aided controls. If the orientation of the active vehicle is maintained constant, the braking maneuvers require simultaneous firing of several jets in a predetermined but constant ration, and this is a non-optimum use of the system.

The safety advantages, of completely avoiding the possibility of an inadvertent collision at a velocity to cause damage, must be evaluated against the potential disadvantages pointed out. This preliminary evaluation indicates that the advantages may be worth the penalties involved. A fuller evaluation of the method, including simulations with visual displays, should be made.

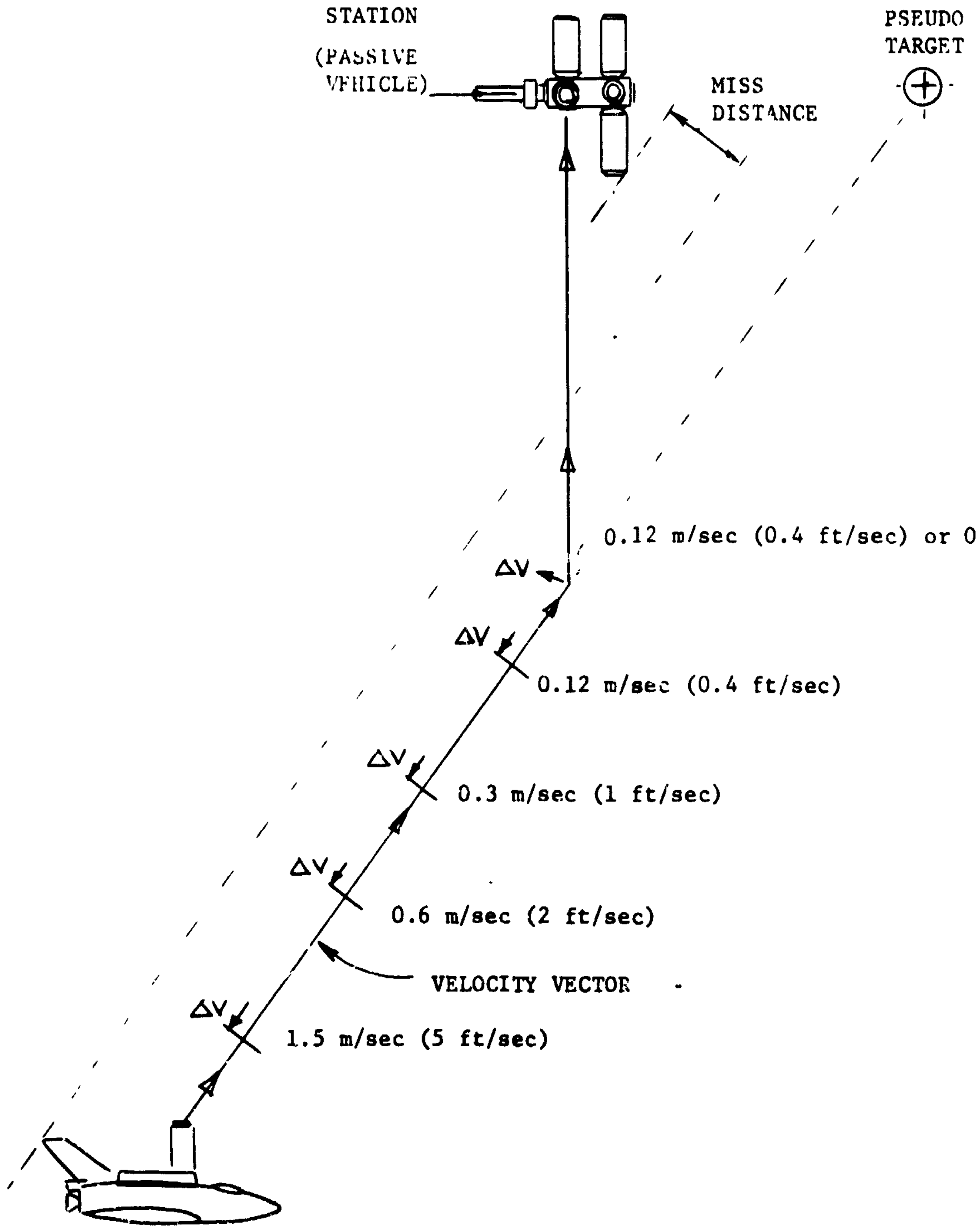


Figure 3-12. Non-collision Docking Approach.

4.0 PERSONNEL TRAFFIC PATTERNS, ESCAPE ROUTES AND ON-BOARD SURVIVABILITY

The purpose of this task was to analyze the personnel traffic patterns, escape route, and on-board survivability from a safety standpoint for the orbiter with crew and passengers, sortie modules, and for the modular space station. Particular situations investigated were normal operations, emergency operations, IVA and EVA.

Generalized candidate configurations, typical of the many variations possible and those which have been or are being considered, were modeled for the orbiter, sortie modules, and modular space station, and evaluated for their ability to satisfy safety requirements which evolved from an analysis of identified credible emergencies.

4.1 CONCLUSIONS AND RECOMMENDATIONS FOR BASELINE ORBITER CONFIGURATION

The safety conclusions and recommendations for the baseline orbiter configuration defined in Phase B studies (Figure 4-1) involve compartmentation, suit provisions, airlock sizing, EVA ingress/egress, and operational and subsystems capability. These are:

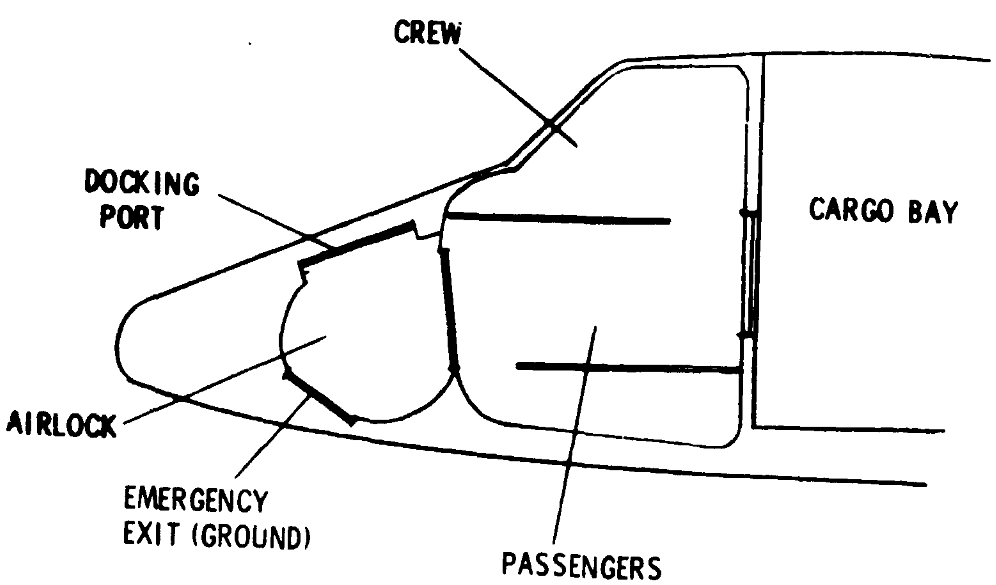


Figure 4-1. Baseline Orbiter Configuration

- Quick-donning pressure suits which do not require prebreathing (8 psi suits) should be provided for all on-board personnel.

- The crew/passenger compartment should be divided into two sections by a partition which can exclude smoke and fumes, and can provide protection against excessive heat from a fire. Pressure build-up beyond the capability of the partition can be provided by suitable pressure relief valves in each section. These sections can provide temporary refuge until corrective measures can be taken.

- All equipment required for return to earth should be capable of operating in a depressurized environment, and of being operated by the crew in pressure suits.

- Capability should be provided for returning from EVA directly into the crew/passenger compartment.

- Provided the above recommendations are implemented, the airlock is not required for safety purposes. It should be available, possibly as a payload item, on missions for which EVA is planned.

- If the airlock is capable of accommodating all passengers in emergency shirtsleeve conditions through deorbit and entry, then 8 psi suits are required only for the orbiter crew on those missions. The passengers have time to return to their seats for landing after reaching low altitudes.

4.2 CONCLUSIONS AND RECOMMENDATIONS FOR ALTERNATE ORBITER CONFIGURATIONS

4.2.1 Configuration with Large Airlock

The airlock requirements for performing EVA are that the airlock be sized to accommodate two men in pressure suits with portable life support systems (PLSS). Such an airlock is likely to be large enough to accommodate four and possibly six men in shirtsleeves.

The airlock for the baseline orbiter which resulted from the Phase B study is even larger than this requirement. It is a sphere of 2.4 m (8 ft) diameter, intercepted by the flat hatches. As shown in Figure 4-2, this airlock can accommodate at least eight men in hammock-type supports under emergency shirtsleeve conditions. Enough room is available for four more men, if desired, making a total of 12 men in the airlock.

Such a large airlock can be used as a second compartment in the event of an emergency. In addition to being sized for two crewmen with PLSS, it must be capable, in an emergency, of supporting all passengers in a shirtsleeve environment through deorbit and reentry. This may require in excess of six hours life support capability in the airlock for return to CONUS (Continental U.S.A.) landing sites. The capability to land with the passengers in the airlock is not required because the passengers can return to the crew/passenger compartment to their respective (or makeshift) landing positions after the

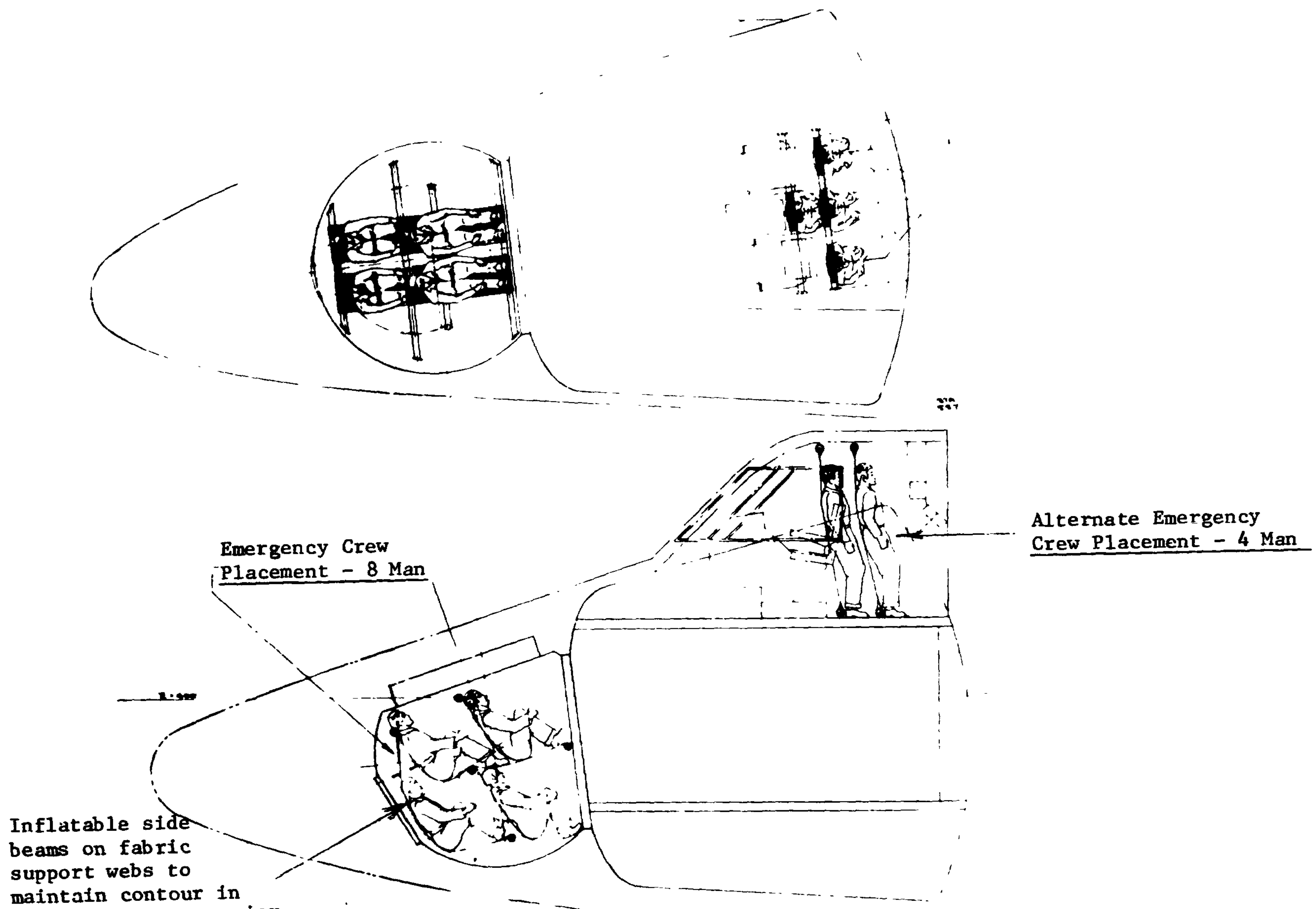


Figure 4.2 Emergency Accommodations in Baseline Orbiter

orbiter re-enters the sensible atmosphere and the cabin is repressurized to a habitable environment. Passenger egress from the airlock could occur at approximately 4500 m (15,000 ft) altitude, 4 minutes prior to landing. Specially sized inward bleed valves on the crew/passenger compartment are required to ensure an adequate repressurization rate.

Two pressure suits only are required in this case for use by the crewmen. These must be quick-donning 8 psi suits, which do not require any pre-breathing. The airlock cannot be used for getting into the suits, as the airlock hatch cannot be opened when shirtsleeve passengers are inside it and the atmosphere in the orbiter has been lost or contaminated. The two suits should therefore be kept in the crew/passenger compartment, not the airlock.

It is estimated that the time required to don 8 psi suits is 7 minutes, or equivalent to the time available in a shirtsleeve environment to cope with pressure loss through a one-inch-diameter hole. Additional reaction time can be gained by employing flood flow control, which replaces the atmosphere at approximately the same rate at which it is being lost, to maintain the atmosphere at the minimum acceptable pressure level.

For missions in which EVA is planned as part of the normal mission, pressure suits must be carried for all the passengers, as well as for the two crewmen and the EVA men. These are required in case an airlock malfunction does not allow repressurization of the airlock (e.g., the external hatch cannot be sealed). The crew and passengers then don their suits, the crew/passenger compartment is then depressurized, and the EVA men can enter. These additional suits may be much simpler than EVA or IVA suits, as no activities are to be performed in them. If the EVA men plan to red-line their oxygen supply to maintain a few hours reserves by the time they return, these additional suits can be 3.5 psi suits which require perhaps two hours of pre-breathing before reducing to the operating pressures. Otherwise, they should be 8 psi suits.

4.2.2 Alternative Orbiter Configuration

An alternative safety approach for the orbiter is shown in Figure 4-3. This configuration is similar to the baseline with the exception that the forward located airlock is eliminated with its volume being absorbed into a single habitable compartment; and special design requirements are imposed to use the floor of the crew compartment to deal with a fire or atmospheric contamination.

The equipment required for return to earth must be capable of operating and being operated in a depressurized condition, as for the baseline configuration.

Pressure suits (8 psi) must be carried for all on-board personnel for all missions.

A portable airlock can be located in the cargo bay for those missions in which EVA is a planned activity. Since suits are provided for all, however, emergency EVA can still be performed from the crew/passenger compartment.

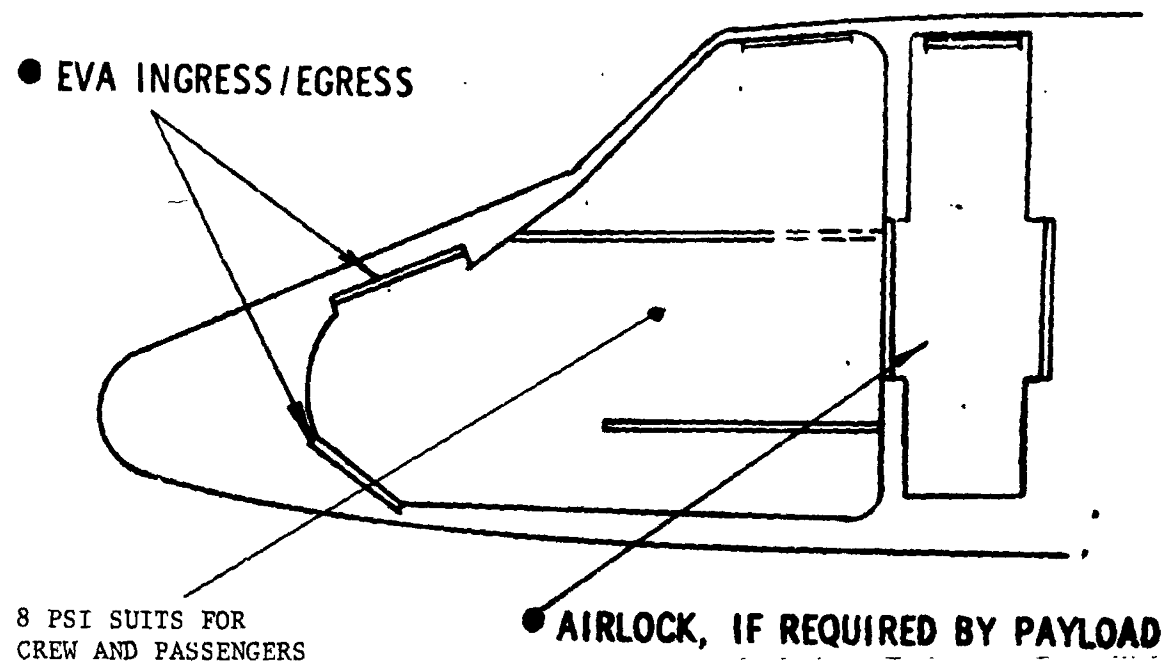


Figure 4-3. Alternative Safety Approach for Orbiter

4.2.3 Ideal Orbiter Configuration

An ideal safety configuration is one in which safety is inherent in the configuration, not through subsystems or time-consuming complicated procedures which may integrally involve personnel. The foremost objectives of such a configuration are (1) to desensitize the vehicle from the potential effects of credible emergencies, (2) to desensitize the vehicle from arbitrary criteria, such as vent valve sizing, factored into subsystems design resulting from a theoretical analysis of the credible emergencies, (3) to minimize the time required to safeguard personnel, and (4) to maximize the time available to perform corrective action.

One configuration which ideally satisfies these objectives relative to the credible emergencies and effects considered in this task, is shown in Figure 4-4. The configuration consists of a crew compartment, a passenger compartment, a two-man airlock, a docking port, three internal hatches, and three external hatches, one of which is a docking port hatch. Two 3.5 psi suits are provided for the two crewmen. Requirements include capability for abort with the passengers in the crew compartment, capability for abort equipment to operate in a vacuum, and capability for abort controls to be operatable by men in pressure suits.

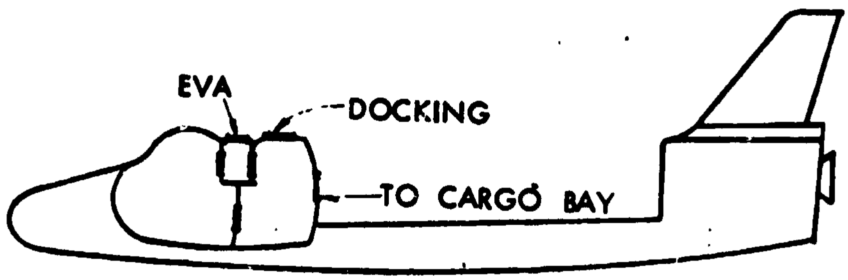


Figure 4-4. Ideal Orbiter Safety Configuration

4.3 CONCLUSIONS AND RECOMMENDATIONS FOR MANNED SORTIE MODULES

Conclusions reached from the analysis for manned sortie modules are:

- A sortie module consisting of two separate pressurized modules does not have any significant safety advantages compared to a single module version. In both cases the orbiter is available as a separate refuge compartment.

- No safety requirement exists for an airlock between a sortie module and an orbiter, provided it is acceptable to abort a particular mission if a depressurization or contamination problem arises in the sortie module. An airlock between orbiter and sortie module could be useful in providing IVA maintenance capability in such an event, but also poses the additional risk of isolating personnel in either vehicle if a similar problem arises in the airlock.

Recommendations made are as follows:

- The airlock, if provided, should be configured such that isolation of the sortie module crew from the orbiter does not result during the performance of EVA from the airlock. If this is not practical, then the emergency capability to deorbit all personnel in the sortie module or in the orbiter should be provided, or the capability should be provided to transfer personnel in the sortie module to the orbiter via EVA to enable an abort of the mission.

- A means of emergency exit (dual egress capability) should be provided in sortie modules, for example, by longitudinal floor providing independent personnel routes above and below the floor.

- Emergency accommodations should be provided in the orbiter for all passengers through an abort.

- A means should be provided to release the sortie module from the orbiter. Release is differentiated from ejection in that no identified credible emergencies require a reaction time less than a few minutes, as implied by ejection.

4.4 CONCLUSIONS AND RECOMMENDATIONS FOR MODULAR SPACE STATION

Conclusions reached for the modular space station are:

- A two-pressure volume configuration, such as provided in the NR design, provides maximum operational flexibility (e.g., mission continuation) in the event of an accident in any one module. Adequate safety can, however, be provided without a two-volume arrangement, but loss of any one module (temporary or permanent) interrupts the mission and may need complex orbiter rescue operations.

- A "closed" configuration which provides at least two independent personnel routes from any one module to any other, provides safety with shirtsleeve operations only. The NR space station design provides such a "closed" configuration by providing auxiliary passages between modules in addition to the main passageway through the core module.

- "Open" configurations, such as the MDAC design, rely on airlocks and IVA, EVA or orbiter rescue to ensure personnel safety in situations requiring emergency evacuation of a module.

- Special precautions must be taken during space station assembly to assure safety of personnel. These precautions include restricting access to station compartments which do not have dual shirtsleeve egress, unlesss the time spent in the compartment is short; potentially hazardous equipment has been checked prior to entry; EVA suits are provided; and a buddy system is employed.

- Space station resupply does not present any unusual safety problems which require unique criteria, requirements, or solutions.

The following recommendations are made:

- Interconnect all modules through an auxiliary passage to provide dual shirtsleeve egress, or where this is impractical, provide a floor in the module which provides for independent personnel routes above and below the floor.

- Design all hatches to be operable from either side to enable escape from within or rescue from outside a module/compartment.

- Interior hatches shall normally be open, with the exception of emergency egress hatches which shall normally be closed.

- Potentially hazardous equipment should not be located in or near areas where maximum crew congestion is likely to occur; e.g., dining/recreation areas.
- Potentially hazardous equipment should not be located in the vicinity of the module docking interface.

4.5 IDENTIFICATION OF CREDIBLE EMERGENCIES

The assessment of escape routes and compartmentation isolation required the identification of credible emergencies from which configuration oriented and supporting requirements could be generated through subsequent hazards analysis.

Eleven credible emergencies were identified and used in the analysis. These are shown in Table 4-1, including their applicability to the vehicles.

Table 4-1. Credible Emergencies

Credible Emergency	Applicability: Orbiter	Sortie Module	Operational Station	Station in Assembly
Fire/toxic environment	X	X	X	X
Explosion	X	X	X	X
Emergency evacuation	X	X	X	X
Loss of pressure	X	X	X	X
Failure to open internal hatch between pressure isolatable volumes	X	X	X	X
Failure to open docking hatch after docking	X	X	X	X
Failure to close docking hatch before undocking	X	X	X	X
Inability to use docking hatch for EVA when EVA required	X		X	
Failure to close external airlock hatch when returning from EVA	X	X	X	
Failure to open internal airlock hatch when returning from EVA	X	X	X	
Failure to close IVA airlock hatch on depressurized/contaminated side or to open hatch on pressurized/habitable side when returning from EVA.			X	

The effects assumed for four of these emergencies, namely, fire/toxic environment, explosion, emergency evacuation, and loss of pressurization, are listed in Table 4-2. This defines the level of these emergencies considered for analysis. For example, the type of fire or toxic environment considered requires rapid (0.5 min) evacuation, but does not result in personnel injury, and allows eventual return to the affected compartment. More severe accidents, which may injure personnel, or which do not allow shirtsleeve return to the affected compartment, are considered under "explosion" and "emergency evacuation".

Table 4-2. Assumed Effects for Variable Level Credible Emergencies

	Minimum Reaction Time (Mins)	Need to Evacuate Compartment	Injured/ Incapacitated Personnel	Restoration to Shirtsleeve Environment	Can Cause Other Listed Credible Emergencies
Fire/Toxic Environment	0.5	Yes	No	Yes	Yes
Explosion	0	Yes	Yes	No	Yes
Emergency Evacuation	5	Yes	No	No	No
Loss of Pressurization	2-8	Yes	No	No	No

4.6 SAFETY ANALYSIS OF ORBITER CONFIGURATIONS

Seven possible orbiter configurations were evaluated for their inherent capability to cope with the credible emergencies identified. The following major assumptions were required to scope the analysis to within workable bounds. These are:

- o Emergencies, other than hatch failures, are not considered on airlocks.
- o Deorbit/return to earth requires crew participation in crew compartment.
- o Rescue vehicle is not available.
- o No double emergencies are considered.
- o Airlocks are sized for two crewmen or all crewmen. If sized for all crewmen, they are treated and evaluated as a second volume.

- o Passage of many personnel through an airlock, two at a time, is not acceptable.

- o Airlock compartment for EVA can be crew compartment, passenger compartment, or airlock.

- o Planned EVA will be accomplished through an airlock.

- o Safety is not achieved via EVA.

Each of the seven candidate orbiter configurations was evaluated, within the constraints of the assumptions, to determine the operational options available to cope with each credible emergency. Analysis of the operational options resulted in secondary configurational, subsystems, and operational requirements necessary to make the option viable.

4.6.1 Candidate Orbiter Configurations

The baseline configuration of the orbiter is composed of an airlock, and a crew and passenger compartment as shown in Figure 4-1. This is the final configuration resulting from the NR Phase B study.

The seven configurations analyzed are shown schematically in Figure 4-5. These are based on the number of practical ways in which the following compartments can be arranged:

- o Crew compartment
- o Passenger compartment
- o Airlock

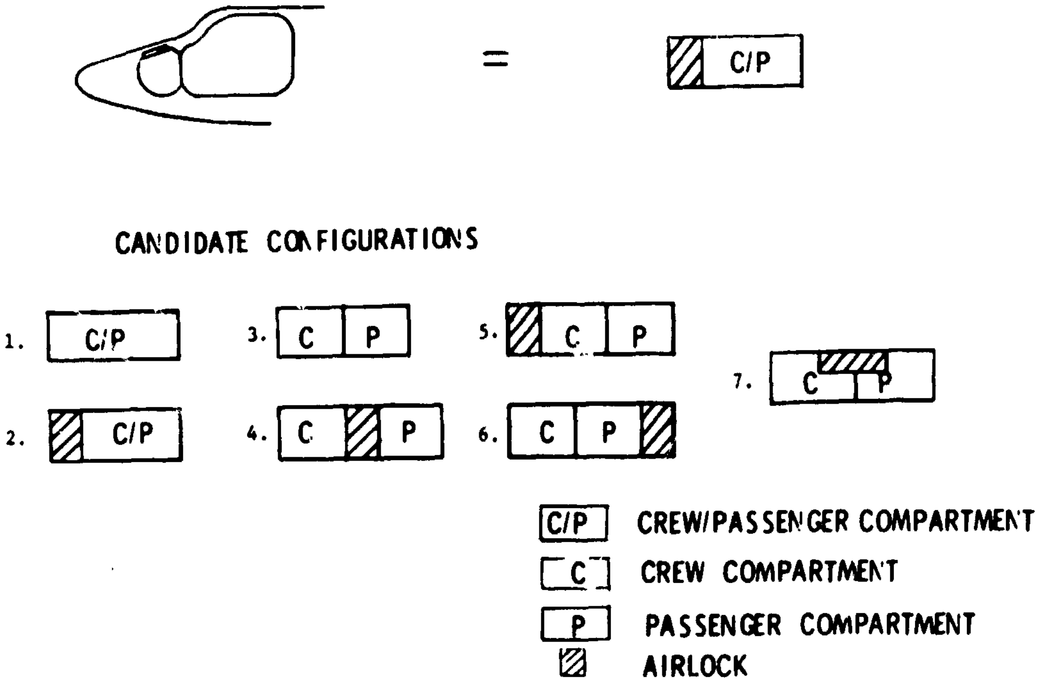


Figure 4-5. Candidate Orbiter Configurations

A hatch, door, or opening may be located anywhere there is a solid line. Compartments which are not habitable, such as the cargo bay, are not included.

4.6.2 Operational Options

The operational options available for four of the emergency situations are shown, together with their applicability to the specific orbiter configurations, in Figures 4-6 through 4-9. The single option, which is universally available for all emergencies is to "take the risk". A program decision not to accept the safety recommendations implies that the risk associated with the emergency is being taken.

4.6.3 Major Safety Requirements

The multitude of options available to cope with each emergency lead to different sets of requirements for each compatible orbiter configuration. These requirements are identified, correlated to the originating emergency, and grouped in accordance with their applicability to each orbiter configuration. A logical reduction of the grouped requirements is made to arrive at a recommended minimum acceptable set for the configuration. This process is illustrated and documented in Figures 4-10 through 4-14.

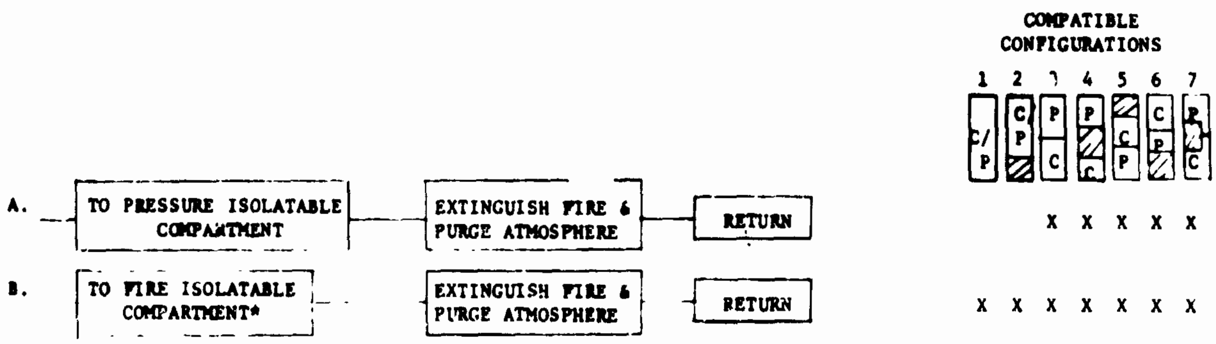
Hatch requirements are an important consideration but are not major configuration drivers and, therefore, all hatch requirements relative to the parameters of location, dual opening (hatch within a hatch) or dual closing (back-to-back) are consolidated under the column titled "Hatch Requirements".

These charts contain sufficient information to ascertain the impact on vehicle configuration of the elimination of one or more requirement options. If, for example, 8 psi suits were eliminated as a viable requirement option on the two compartment with airlock orbiter configurations due to a programmatic decision, the remaining viable alternatives could readily be determined, as shown by Figure 4-14.

A summary of the recommended requirements for all seven candidate orbiter configurations is shown in Figure 4-15. Only one configuration, the two-compartment with an airlock in between, is identified as not acceptable, because a problem in the airlock can isolate the passengers from the crew compartment.

4.6.4 Evaluation of Configurations

Five basic options were identified for comparing the configurations to arrive at relative safety ratings. These relate to the number and type of suits; whether IVA or EVA is required to effect transfer of personnel from the affected compartment to the crew compartment in the event of an emergency; and whether a refuge compartment is available. These five options are:



* ISOLATES ATMOSPHERE, BUT NO SIGNIFICANT ΔP CAPABILITY

Figure 4-6. Options - Fire/Toxic Environment

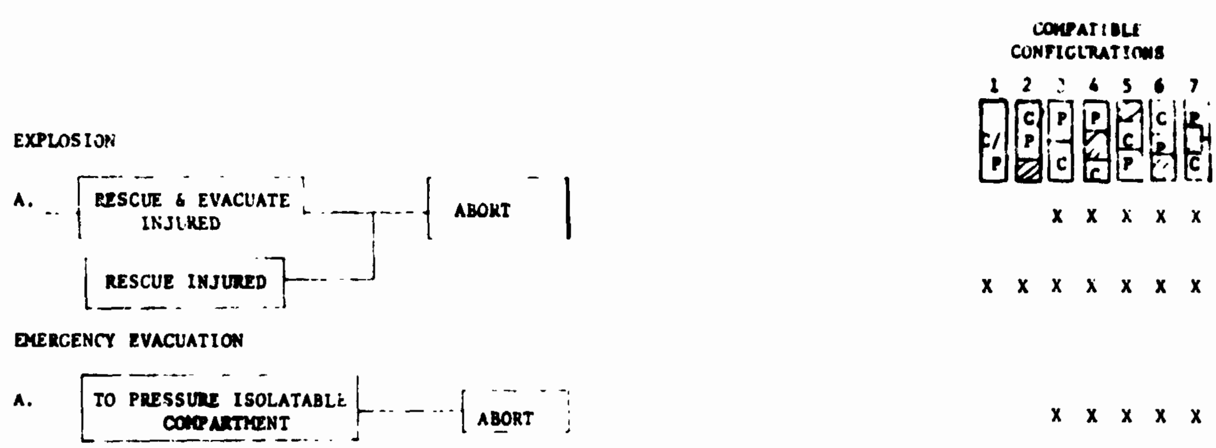
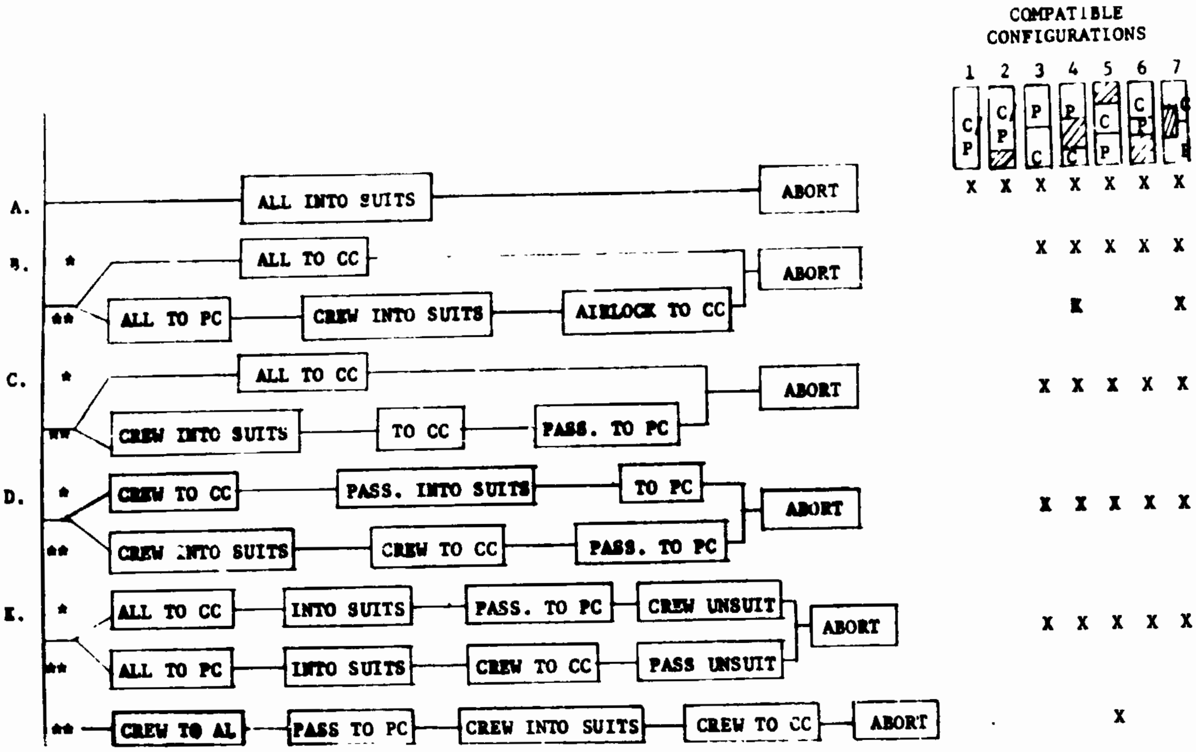
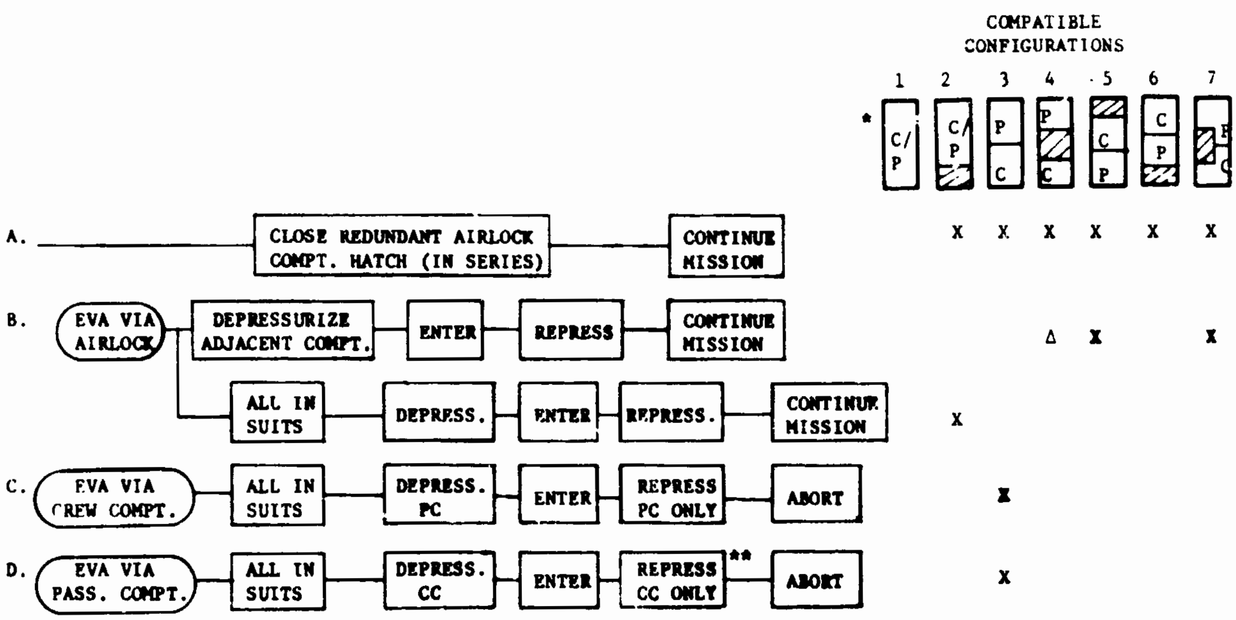


Figure 4-7. Options - Explosion and Emergency Evacuation



* PASSENGER COMPARTMENT (PC) DEPRESSURIZED
** CREW COMPARTMENT (CC) DEPRESSURIZED

Figure 4-8. Options - Loss of Pressure



* NO PLANNED EVA FOR SINGLE CREW/PASSENGER COMPARTMENT
** PASSENGERS STAY SUITED IN PASS. COMPT. OR SHIRTSLEEVE IN CREW COMPT.
Δ SEE TEXT

Figure 4-9. Options - Failure to Close External Airlock Hatch When Returning From EVA (Resulting in Inability to Return From EVA)

Emergency/ Failure	Fire Isol. Compt.	Suits for All	8 psi Suits	Abort in Vacuum: Crew	Abort in Vacuum: Pass.	Pass. Abort in Crew Compt.	Hatch Reqmts**	
Fire/Toxic Environment	X							
Explosion								
Emergency Evacuation			--	RISK	--			
Loss of Pressure		X	X	X	X			
Fail to Close External EVA Hatch			--	N/A	--			
Fail to Open Internal EVA Hatch			--	N/A	--			
Fail to Close Docking Hatch for Undocking		X					X	} or
Inability to Use Docking Hatch for EVA when EVA Required							X	
RECOMMENDED	X	X	X	X	X		X	

CONFIGURATION

1. C / P

X = Requirement
**Redundant Opening, Closing; Location

Figure 4-10. Major Safety Requirements, Crew/Passenger Compartment Only

Emergency/ Failure	Fire Isol. Compt.	Suits for All	8 psi Suits	Abort in Vacuum: Crew	Abort in Vacuum: Pass.	Pass. Abort in Crew Compt.	Hatch Reqmts*	
Fire/Toxic Environment	X							
Explosion								
Emergency Evacuation			--	RISK	--			
Loss of Pressure		X	X	X	X			
Fail to Close External EVA Hatch		X					X	} or
Fail to Open Internal EVA Hatch							X	
Fail to Close Docking Hatch for Undocking		X		X	X		X	} or
Inability to Use Docking Hatch for EVA when EVA Required		X					X X	} or
RECOMMENDED	X	X	X	X	X		X	

CONFIGURATION

2. AL | C / P

X = Requirement
* Redundant Opening, Closing; Location

Figure 4-11. Major Safety Requirements, Crew/Passenger Compartment With Airlock Only

Emergency/ Failure	Fire Isol. Compt.	Suits for All	8 psi Suits	Abort in Vacuum: Crew	Abort in Vacuum: Pass.	Pass. Abort in Crew Compt.	Hatch Reqmts*	
Fire/Toxic Environment								Evacuate to Adjacent Compartment
Explosion								
Emergency Evacuation								
Loss of Pressure		X	X	X	X			
			X	X		X		or
		X	X	X	X	X		
		X		X	X			
Fail to Close External EVA Hatch							X	
		X		X				or
		X			X			
Fail to Open Internal EVA Hatch							X	
Fail to Close Docking Hatch for Undocking							X	
						X		
		X			X			or
				X				
Inability to Use Docking Hatch for EVA when EVA Required							X	
RECOMMENDED			X	X		X	X	
		X		X	X		X	or

X = Requirement
* Redundant Opening, Closing; Location

CONFIGURATION

3. | C | P |

Figure 4-12. Major Safety Requirements, Separate Crew and Passenger Compartments

Emergency/ Failure	Fire Isol. Compt.	Suits for All	8 psi Suits	Abort in Vacuum: Crew	Abort in Vacuum: Pass.	Pass. Abort in Crew Compt.	Hatch Reqmts*	
Fire/Toxic Environment								Evacuate to Adjacent Compartment
Explosion								
Emergency Evacuation								
Loss of Pressure		X	X	X	X			
				X		X	4,5,7	or
			X	X		X		
		X		X	X			
Fail to Close External EVA Hatch							X	
Fail to Open Internal EVA Hatch							X	
Fail to Close Docking Hatch for Undocking							X	
						X		
		X			X			or
				X				
Inability to Use Docking Hatch for EVA when EVA Required							X	
RECOMMENDED	-- SEE FOLLOWING CHARTS --							

X = Requirement
**Redundant Opening, Closing; Location

CONFIGURATION

6. | C | P | AI |

7. | C | AL | P |

5. | AL | C | P |

4. | C | AL | P |

Figure 4-13. Major Safety Requirements, Separate Crew, Passenger and Airlock Compartments

Emergency/ Failure	Fire Isol. Compt.	Suits for All	8 psi Suits	Abort in Vacuum: Crew	Abort in Vacuum: Pass.	Pass. Abort in Crew Compt.	Hatch Reqmts*	
Fire/Toxic Environment								Evacuate to Adjacent Compartment
Explosion								
Emergency Evacuation								
Loss of Pressure		X		X X	X	X	4,5,7	or
Fail to Close External EVA Hatch							X	
Fail to Open Internal EVA Hatch							X	
Fail to Close Docking Hatch for Undocking		X		X	X	X	X	or
Inability to Use Docking Hatch for EVA when EVA Required							X	
VIABLE REQUIREMENTS SETS		X		X X	X	X	X X	or
RECOMMENDED				X		X	X	

CONFIGURATION

6. C | P | AL

7. C | AL | P

5. AL | C | P

4. C | AL | P

Figure 4-14. Effect of Elimining 8 psi Suits (Reference Figure 4.2-4D)

Configuration	Fire Isol. Compt.	Suits for All	8 psi Suits	Abort in Vacuum: Crew	Abort in Vacuum: Pass.	Pass. Abort in Crew Compt.	Hatch Reqmts*	
C / P	X	X	X	X	X		X	
C / P	X	X	X	X	X		X	
C | P		X	X	X X	X	X	X X	or
C | P		X	X	X X X	X	X X	X X X	or
C | P		X	X	X X	X	X	X X	or
C | P				X		X	X	
C | P	-- NOT RECOMMENDED --							

Figure 4-15. Summary of Recommended Requirements

Option	Pressure Suits Quantity	Pressure Suits Type	Transfer Mode to Crew Compartment	Refuge Compartment Available
A	All	8 psi	N/A	No
B	2	8 "	N/A	Yes
C	All	3.5 "	IVA	Yes
D	2	3.5 "	IVA	Yes
E	2	3.5 "	EVA	Yes

A comparison of the configurations, using these options, as primary parameters, is shown in Figure 4-16. An additional parameter, that of reaction time, is introduced to signify the amount of time available to react to the credible emergencies. Seven minutes corresponds to the time required for obtaining access to and donning 8 psi suits. Two minutes is the time required for personnel to evacuate, in a shirtsleeve environment, an affected compartment and seek refuge in the adjoining compartment.

The safety ratings as listed are based on the reaction time and availability of a rescue compartment. Options which result in minimum reaction time and exhibit a rescue compartment are most favorable. The acceptable, good, and best ratings apply to the combination of a particular configuration and the number and type of pressure suits carried on-board. The ratings are based on the resulting capabilities of the configuration/suit combinations, as follows:

Safety Factor: Reaction Time	Refuge Compartment	Safety Rating
7 minutes	No	Acceptable
7 minutes	Yes	Good
2 minutes	Yes	Best

CONFIGURATION	OPTION	PRESSURE SUITS QTY.	PRESSURE SUITS TYPE	SAFETY FACTORS REACTION TIME*	SAFETY FACTORS REFUGE COMPT.	SAFETY RATING
1. C P	A	ALL	8 PSI	7 MINS	NO	ACCEPTABLE
2. C P	A	ALL	8 PSI	7 MINS	NO	ACCEPTABLE
3. C P	B	2	8 PSI	7 MINS	YES	GOOD
	C	ALL	3.5 PSI	2 MINS	YES	BEST
4. C P	D	2	3.5 PSI	2 MINS	YES, IF ACCESSIBLE	POOR **
5. C P	B	2	8 PSI	7 MINS	YES	GOOD
	C	ALL	3.5 PSI	2 MINS	YES	BEST
	D	2	3.5 PSI	2 MINS	YES	BEST
6. C P	B	2	8 PSI	7 MINS	YES	GOOD
	C	ALL	3.5 PSI	2 MINS	YES	BEST
	E	2	3.5 PSI (EVA)	2 MINS	YES	BEST
7. C P	D	2	3.5 PSI	2 MINS	YES	BEST

* REACTION TIME TO ACHIEVE SAFETY: 7 MINS TO DON SUITS; 2 MINS TO EGRESS TO REFUGE COMPT
** AIRLOCK PROBLEM CAN PREVENT ACCESS TO CREW COMPARTMENT

Figure 4-16. Comparison of Configurations

4.7 SAFETY ANALYSIS OF SORTIE MODULE CONFIGURATIONS

Evaluation of the sortie module configurations is involved with the effects of the sortie module configuration on orbiter personnel and vehicle safety and, conversely, with the use of the orbiter as a refuge volume for sortie module personnel. This task consideres only manned sortie modules attached to the orbiter.

4.7.1 Candidate Sortie Module Configurations

The six candidate sortie module configurations shown in Figure 4-17 were selected for evaluation.

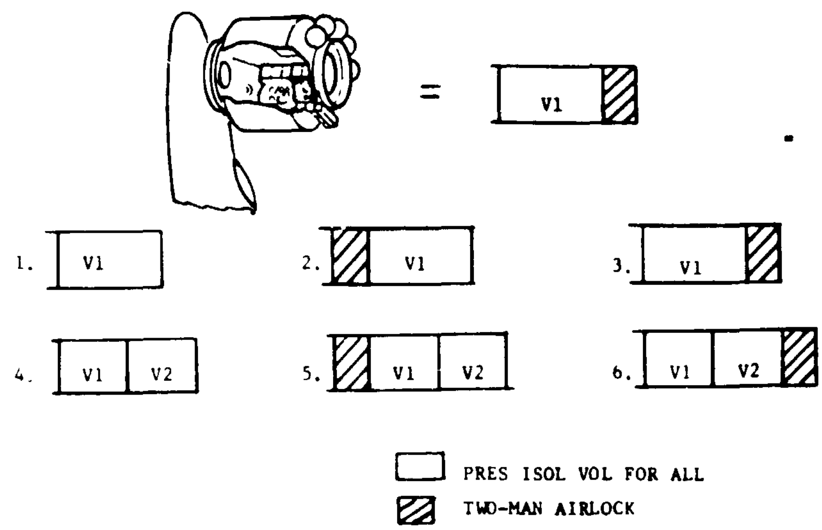
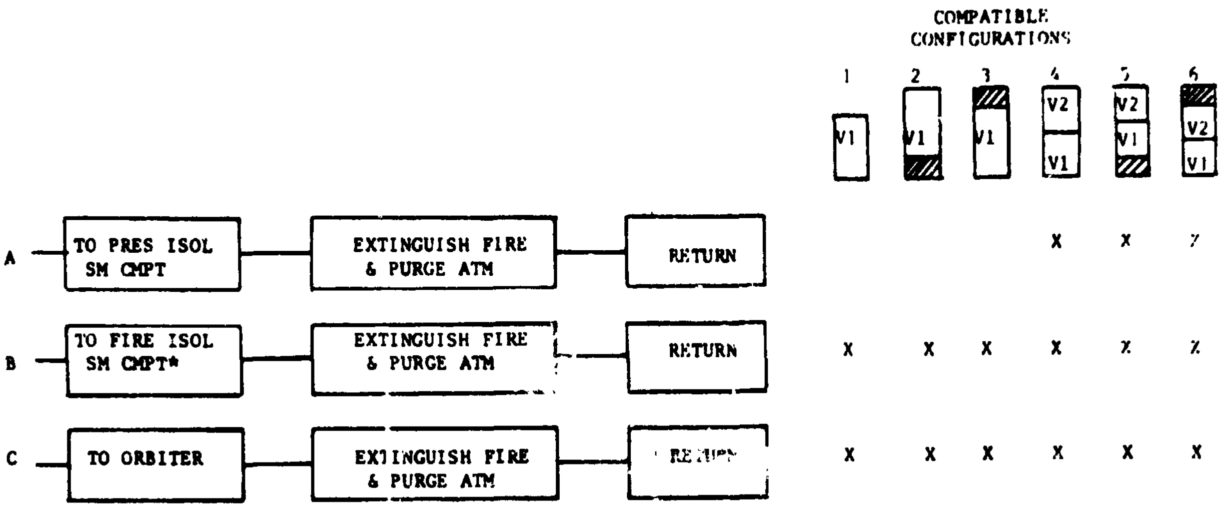


Figure 4-17. Candidate Sortie Module Configurations

4.7.2 Operational Options

The operational options available to cope with three credible emergencies are shown for each of the candidate sortie module configurations in Figures 4-18 through 4-20. Again, as for the orbiter analysis, an option which is universally available for all emergencies is to "take the risk". A program decision not to accept the safety recommendations implies that the risk

associated with the emergency is being taken. A second option which is universally available for all sortie module emergencies is to use the orbiter for refuge.



*Isolates atmosphere, but no significant delta-P capability

Figure 4-18 Options - Fire/Toxic Environment

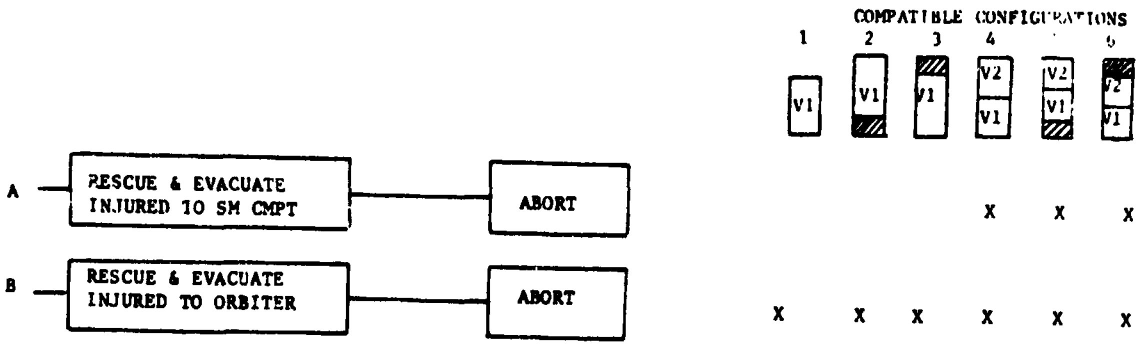


Figure 4-19 Options-Explosion

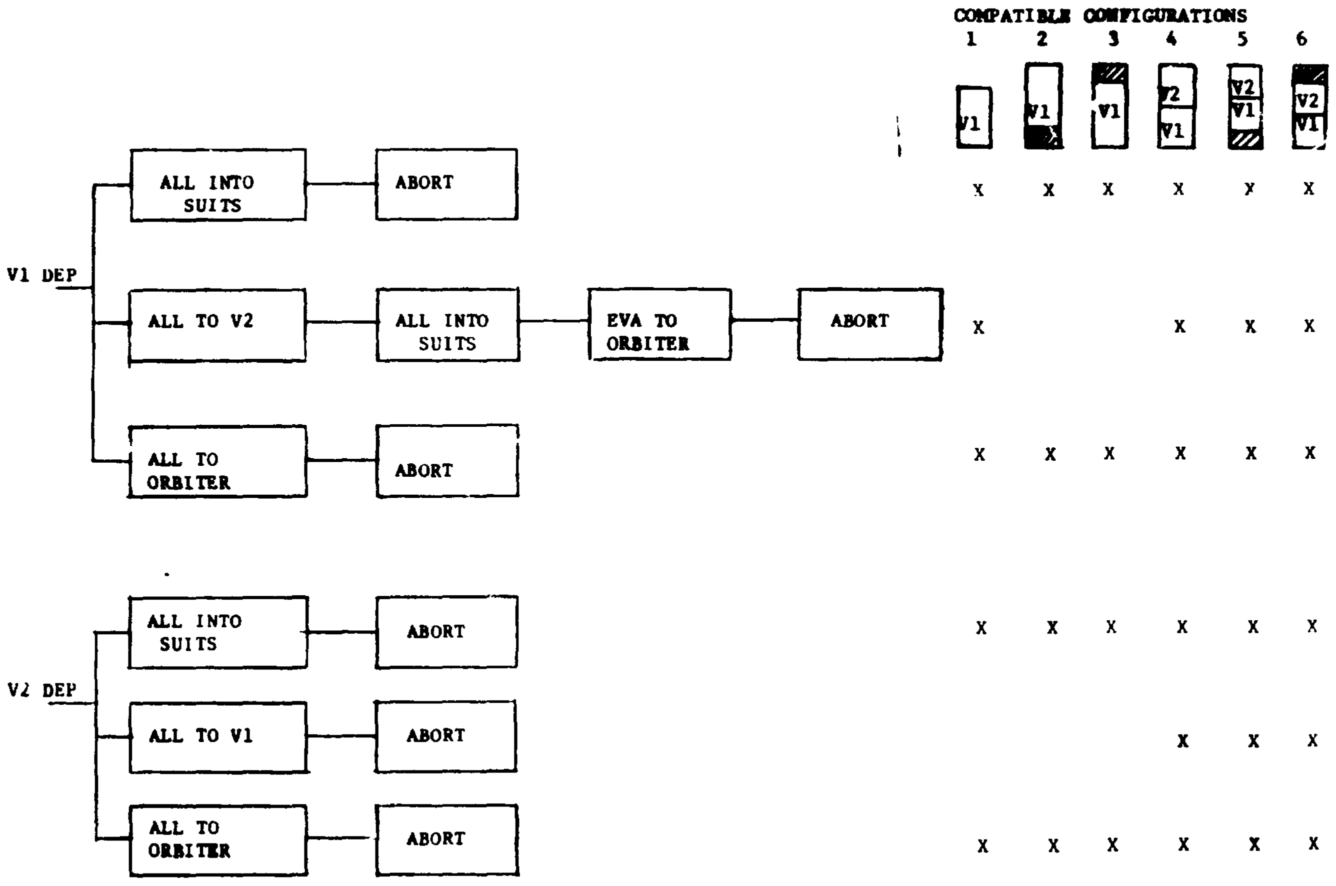


Figure 4-20. Loss of Pressure

4.7.3 Major Safety Requirements

The operational options of the previous section were evaluated to arrive at major safety requirements for each candidate sortie module configuration. The recommended requirements are summarized in Figure 4-21.

Sortie Module Configuration	Fire Isol Compt	Suits for All	8 PSI Suits	Pers Abort in Vacuum in SM	Personnel Shirtsleeve Refuge/Abort: SH***	Personnel Shirtsleeve Refuge/Abort: Orbit.	EVA To/ From Orbiter**	IVA To/ From Orbiter	Hatch Reqmts* ***	
1. V1						X X	X		X	or
2. V1					X	X X	X		X	or
3. V1						X X	X		X	or
4. V1 V2					X	X X	X		X	or
5. V1 V2					X	X X	X		X	or
6. V1 V2						X X	X		X	or
Common to All						X X	X		X	or
Required for All						X				

X = Requirement
* = Redundant Opening, Closing; Location
** = Applies only if EVA is performed from Sortie Module
*** = Only applies if EVA is performed or internal hatch is normally closed

Figure 4-21. Summary of Recommended Requirements

Only four requirements are involved in the recommendation. These are personnel shirtsleeve refuge/abort in the orbiter, personnel shirtsleeve refuge/abort in the sortie module, EVA to and from the orbiter, and hatch requirements. Of these requirements, only one, the requirement for personnel shirtsleeve rescue/abort in the sortie module is not common to all configurations.

The only requirement which is common to all candidate configurations and recommended sets of requirements is that of personnel shirtsleeve refuge/abort in the orbiter. The underlying rationale for recommending this requirement is that regardless of the sortie module configuration, exit to and refuge in the orbiter is the natural goal for emergencies which do not cut off the normal egress path to the orbiter.

4.7.4 Emergency Egress to Orbiter from Sortie Module

Three basic configuration concepts, shown in Figure 4-22 are available for providing emergency egress to the orbiter for an emergency, such as a fire or explosion, which has blocked the normal egress route.

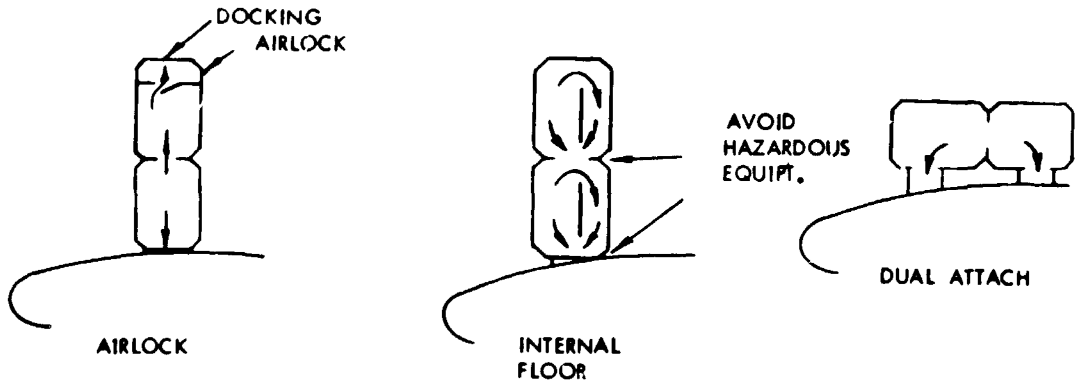


Figure 4-22. Emergency Egress From Sortie Module

The second concept is recommended as being the most practical one. This is similar to that employed on the NR modular space station modules and uses an internal floor to divide the module horizontally into two basic volumes. Access doors (or openings) are provided in the floor at each end of the module with sufficient clearance underneath the floor to allow shirtsleeve personnel to maneuver to the exit at the orbiter interface and egress.

4.8 SAFETY ANALYSIS OF MODULAR SPACE STATION CONFIGURATIONS

The NR and MDAC modular space station configurations resulting from Phase B studies were evaluated for the inherent means available to cope with the identified credible emergencies. Normal operations of the space station in between resupply operations, the space station assembly, and the resupply operations were considered.

The analysis assumes that each of the credible emergencies can occur in any of the modular elements and that each modular element and the orbiter, when attached to the station, is a pressure isolateable volume compartment. The credible emergencies considered lead to a number of basic criteria, which are described below.

4.8.1 Dual Egress

Certain emergencies in a module, such as fire or explosion, may cut off the normal escape route to a survivable area resulting in entrapment of the crew within the affected module. The possibility of isolating personnel in a compartment in which an emergency has occurred can be reduced if multiple egress paths to a survivable area are provided within a habitable compartment. The desirability of these provisions, from the safety point of view, lead to the dual egress criterion which is stated as:

- o Normally habitable compartments of more than 25 m^3 (880 ft^3) in volume shall have two or more exits into areas which provide for personnel survival.

The volume below which the dual egress criterion does not apply, 25 m^3 (880 ft^3), is determined by judgment and is intended to represent the minimum compartment volume below which the immediately dangerous space (heat, flames, debris) in a credible emergency would prevent crew escape and survival, regardless of the number of egress routes.

Four conceptual means of satisfying the dual egress criterion for the modular space station are available:

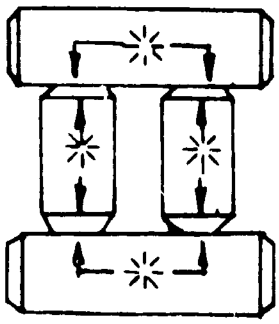
A. **Dual shirtsleeve entry/egress inherent in the configuration through the interconnection of modular elelements, in a closed "ring" configuration.**

B. External connecting passages, called auxiliary passages, required between proximate modules to provide the second shirtsleeve egress path.

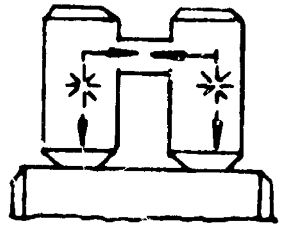
C. Module floors which provide escape routes above and below the floor.

D. Airlocks with docking capability for rescue by the orbiter, or with sufficient suits for EVA escape/rescue, are required.

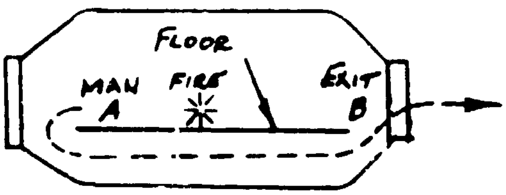
These concepts are shown schematically in Figure 4-23.



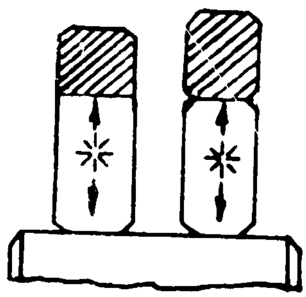
A. CLOSED RING CONFIGURATION



B. AUXILIARY PASSAGE



C. FLOOR IN MODULE



D. AIRLOCKS ON MODULES

Figure 4-23. Alternate Solutions for Satisfying Dual Egress Criterion

Both the NR and MDAC stations can meet the dual egress criterion by one or more of the above means as can be seen from Figure 4-24.

4.8.2 Dual Ingress

Emergencies may occur which may result not only in incapacitating personnel but also in cutting off the rescue path or opening. Because personnel may be injured or incapacitated, the time involved to effect rescue may be a critical factor for crew survival, and participation of the injured personnel in the rescue operations cannot be assumed. Consideration of these possible effects of credible emergencies leads to the dual ingress criterion:

- Access to two or more shirtsleeve entraces into normally habitable compartments or more than 25 m^3 (880 ft^3) in volume shall be immediately available from each of the other normally inhabited compartments.

Rationale for the volume constraint on applicability of the criterion is identical to that previously discussed for dual egress.

The primary difference between the dual egress and dual ingress criteria is that dual egress can be satisfied by IVA or EVA, while dual ingress can only be satisfied because of time criticality, by shirtsleeve operations.

The ing . paths available for both subject stations are shown in Figure 4-25. As shown, an incapacitated crewman in a life support or control module docked to the core on the NR station can be reached in a shirtsleeve environment either by the docking port or auxiliary passage openings. On the MDAC station, an incapacitated crewman in either end of the crew/operations module, or in a module docked to the crew/operations module, can be reached via only one shirtsleeve path and as such does not satisfy the d ' ingress criterion.

4.8.3 Loss of a Module/Compartment

An emergency in a module/compartment can render life support and station control facilities in the module/compartment totally inoperable and unrepairable or, in a less extreme case, temporarily inoperable until repairs can be effected.

This situation leads to a module/compartment safety criterion as follows:

- Capability shall be provided for the emergency shirtsleeve survival of all on-board personnel until the next resupply or emergency shuttle flight following the loss of access to any one module/compartment and the loss of equipment and supplies in that module/compartment. If the loss of the module/compartment divides the station into two or more isolated habitable sections, then each section shall provide the survival capability for all on-board personnel, including an available docking port.

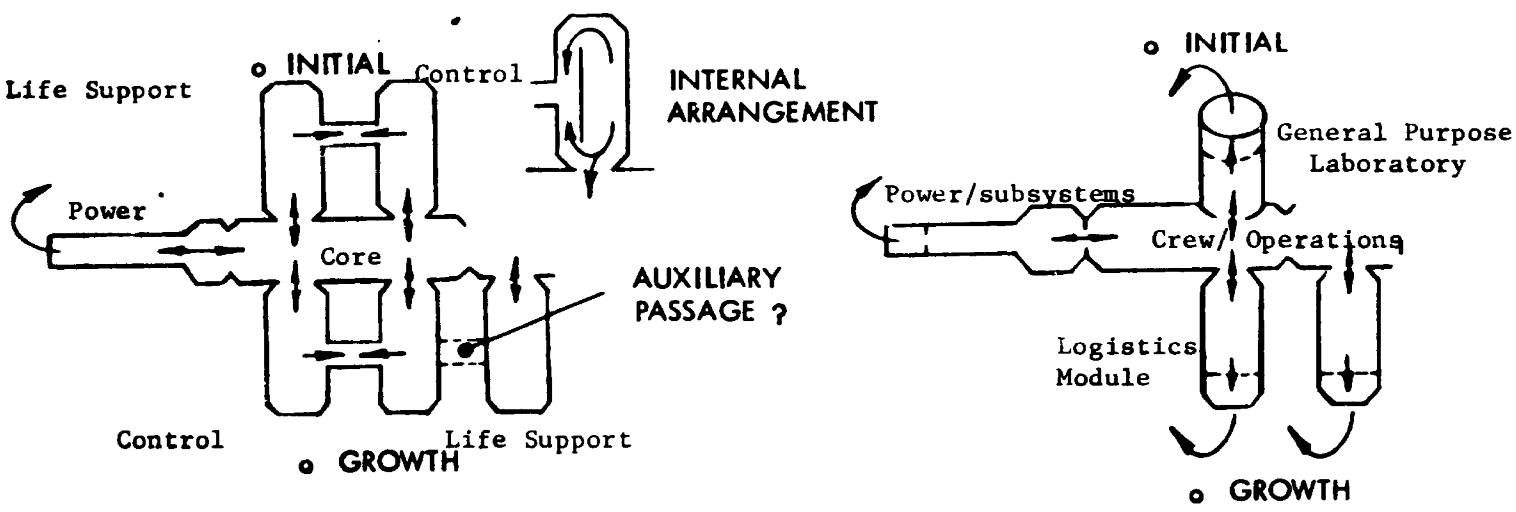


Figure 4-24. Dual Egress Criterion

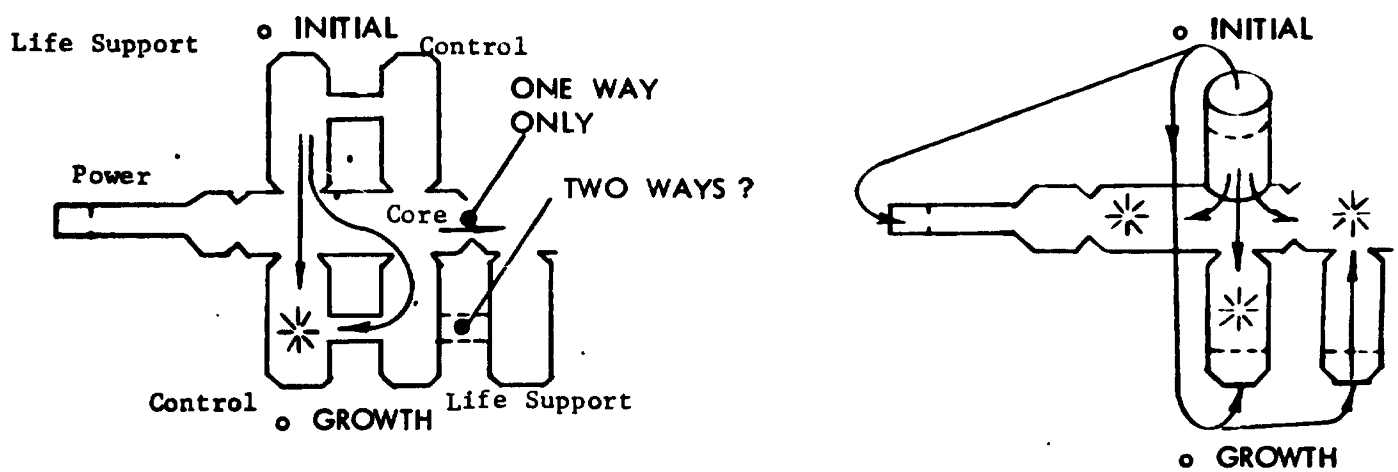


Figure 4-25. Dual Ingress Criterion

This survival volume can be composed of a pressure isolatable compartment within a module, a whole module, or a cluster of modules.

The loss of a module/compartment criterion is satisfied by the NR station as can be seen from Figure 4-26. The NR station is divided into two separate pressure isolatable volumes by the airlock (AL) on the core module.

On the MDAC station, the separate volumes of the crew/operations module and the general-purpose laboratory serve as survival volumes for one another. Access between these two modules, should one become depressurized, would be through an IVA airlock formed by the hatches of each module at their docking interface.

The modular arrangement does not, however, satisfy via a shirtsleeve environment, the part of the loss of a module/compartment criterion which deals with division of the station into two or more isolated volumes. A potential hazard with this modular arrangement is that loss of the crew/operations module could isolate the crew in separate modules if, for example, personnel were working in the power/subsystems module, cargo module, or a module or cluster of modules docked to the end of the crew/operations module. The only modes available to reunite the crew would be for stranded members to perform IVA through the crew/operations module using the hatch-formed airlocks or to perform EVA to gain access to the genera-purpose laboratory through its end-located internal airlock. Either return mode is disadvantageous in that it requires storage and dispersement of IVA/EVA suits and critical equipment and supplies throughout the vehicle.

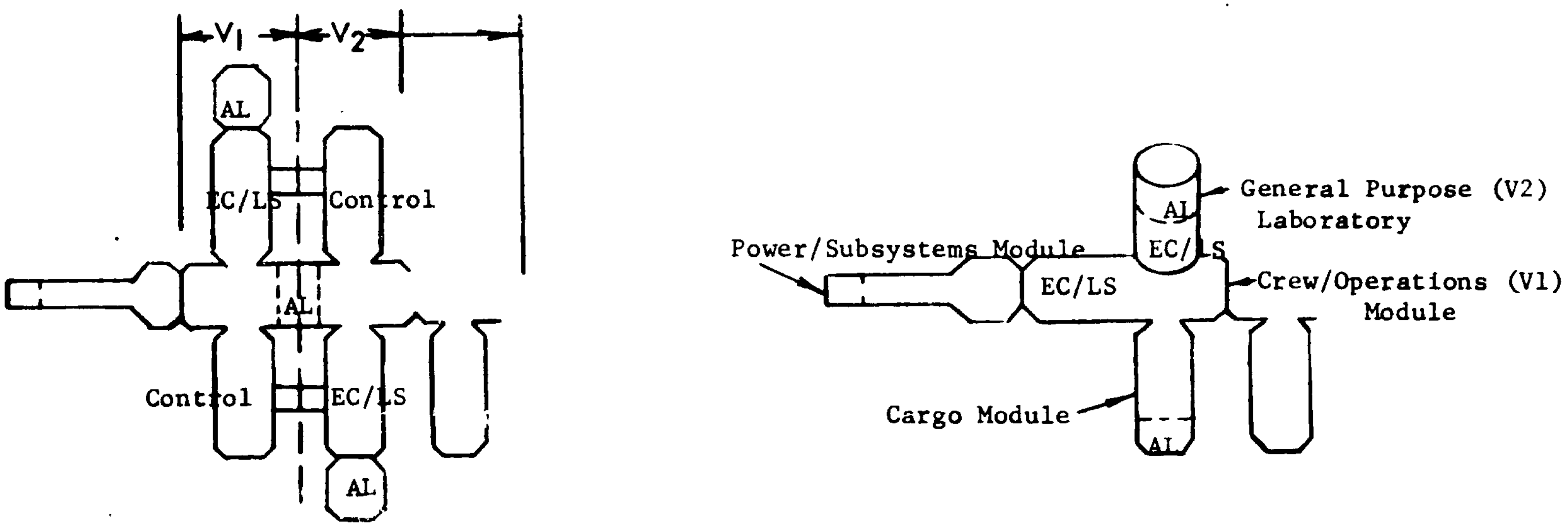


Figure 4-26. Loss of a Module/Compartment Criterion

5.0 ANALYSIS OF DISABLED SPACECRAFT IN A TUMBLING MODE

Uncontrolled tumbling of a spacecraft following loss of its capability to control its attitude is one of the most critical emergency situations that could arise in space. For a vehicle with reentry capability, such as a shuttle orbiter, neither deorbit nor reentry would be possible under these conditions. A rescuing vehicle may be unable to help the tumbling vehicle because it cannot dock to it. Such a situation could, therefore, be catastrophic, and result in loss of both the vehicle and its occupants. If the tumbling vehicle contained a sizeable source of radioactive material, e.g. in a nuclear reactor, an unacceptable risk to the population at large may exist from the eventual random re-entry of the vehicle into the earth's atmosphere.

The purpose of this task was to examine possible methods for arresting the motion of an out-of-control tumbling spacecraft by means external to the vehicle in order to save the onboard personnel and, if possible, the spacecraft; and to determine the feasibility and establish requirements for personnel escape in the event the tumbling cannot be arrested. The tumbling spacecraft considered includes the shuttle orbiter, the space station, and individual modules, called Small Space Vehicles (SSV's) for this study. Sortie modules or space station modules are typical of SSV's in size, mass properties and geometry. The tumbling vehicle was essentially considered disabled and non-cooperative, so that use of onboard subsystems or personnel to assist in arresting the tumbling was not considered.

The rescuing vehicle was considered to be a shuttle orbiter with an appropriate payload. All the concepts considered for arresting the tumbling could, however, equally well be used in a remotely controlled mode from an unmanned tug brought up in a shuttle orbiter. This may be applicable in cases where the tumbling vehicle presents an unacceptable hazard to the orbiter (e.g., if breakup of the tumbling vehicle is possible, or a high radiation environment is present), or for orbits beyond the orbiter capability. For the case where the onboard personnel have to abandon the tumbling vehicle, however, a shuttle orbiter or other rescue vehicle with life support capability was assumed to be in the immediate vicinity of the tumbling spacecraft. Also the men were assumed to be in communication with the rescuing vehicle, to each have a pressure suit with portable life support, and an operable hatch which they can open to space for extravehicular activity (EVA) transfer to the rescuing vehicle.

5.1 CONCLUSIONS AND RECOMMENDATIONS

5.1.1 Arresting the Motion of a Tumbling Spacecraft

Two preferred concepts for arresting the motion of tumbling spacecraft are shown in Figure 5-1. These are:

- The water stream concept, in which a jet of water is directed at the tumbling spacecraft
- The stick-on rocket concept in which small solid rockets are directed at the tumbling spacecraft and fire upon contact

General conclusions reached are:

- Feasible, low development cost, operationally practical concepts for arresting the motion of out-of-control tumbling vehicles have been identified.
- The preferred concepts can be operated with an adequate margin for the worst cases of tumbling orbiter, modular space station, and small manned space vehicles considered using only one emergency shuttle orbiter launch with the de-tumbling device as a payload.
- The preferred concepts are adaptable for remote use on unmanned tugs, to reach and arrest the motion of smaller satellites and spacecraft in orbits which cannot be reached by the shuttle orbiter alone.
- The water stream concept (Figure 5-1A) appears to be the most attractive of the concepts identified. It can be developed from off-the-shelf, non-spacecraft hardware; have large factors of safety and margins to minimize the necessity for extensive qualification, since weight is not critical; it can be stored at the launch site or sites of the shuttle for long periods without any upkeep costs, and be made ready for use in a matter of hours; it can deal with any configuration and size of spacecraft; it poses no safety problems to the shuttle or the tumbling vehicle; it should cause no damage to the tumbling spacecraft except possibly to delicate appendages such as solar panels; it has only minor development risks; and its operation and use is simple, tolerant of errors, and probably requires little training.
- The stick-on rocket concept (Figure 5-1B) also appears attractive. It can use existing solid rocket motors to minimize development costs; it is a light enough system that a single shuttle flight can ensure a large "over-kill" ratio; a long, low maintenance storage life is practical at each shuttle launch site; it can be ready for launch within hours; like the water stream, it can deal with any configuration and size of spacecraft; and its operation and use is simple, tolerant of error and probably requires little training.

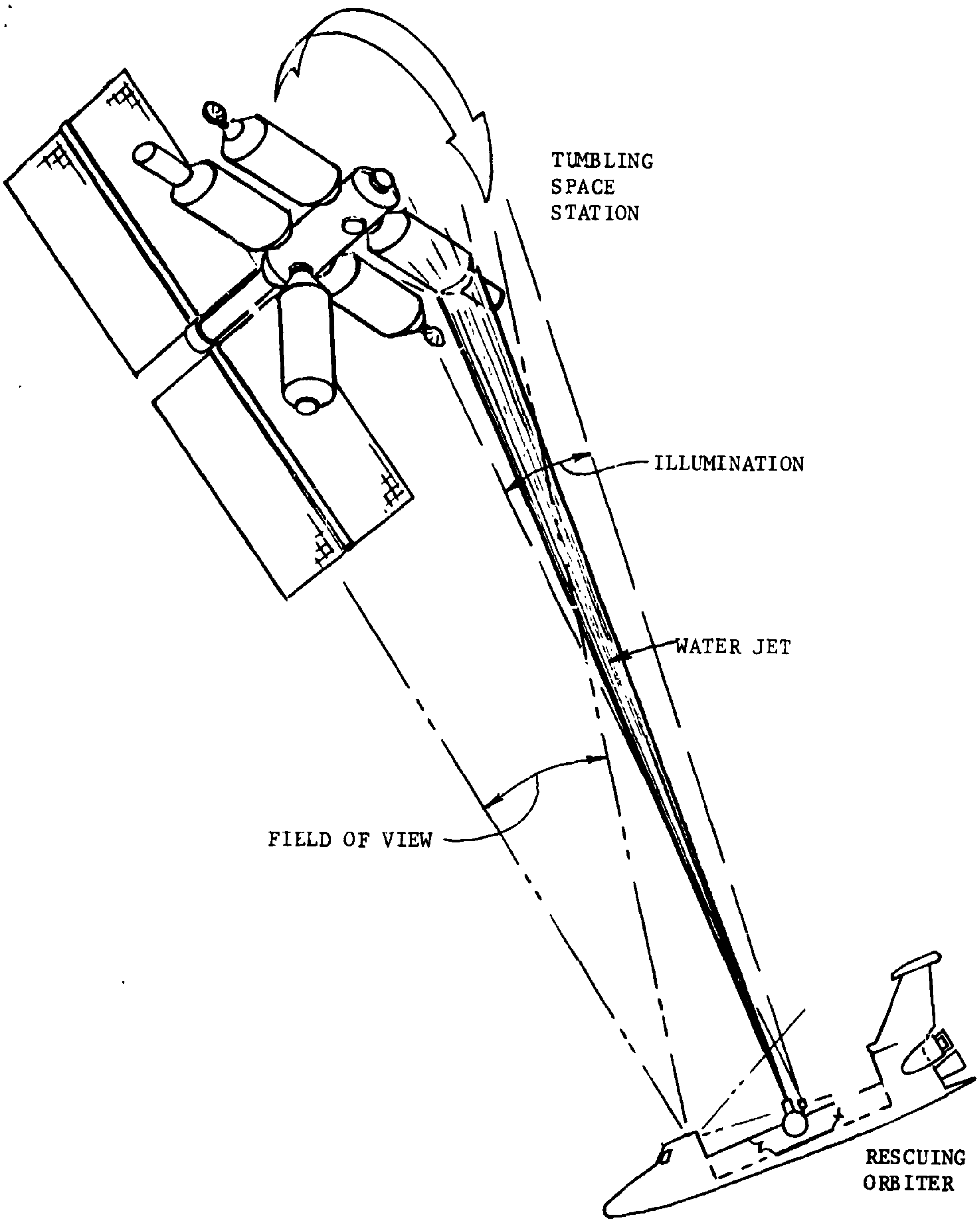


Figure 5-1A. Water Stream Concept Used to Arrest a Tumbling Space Station

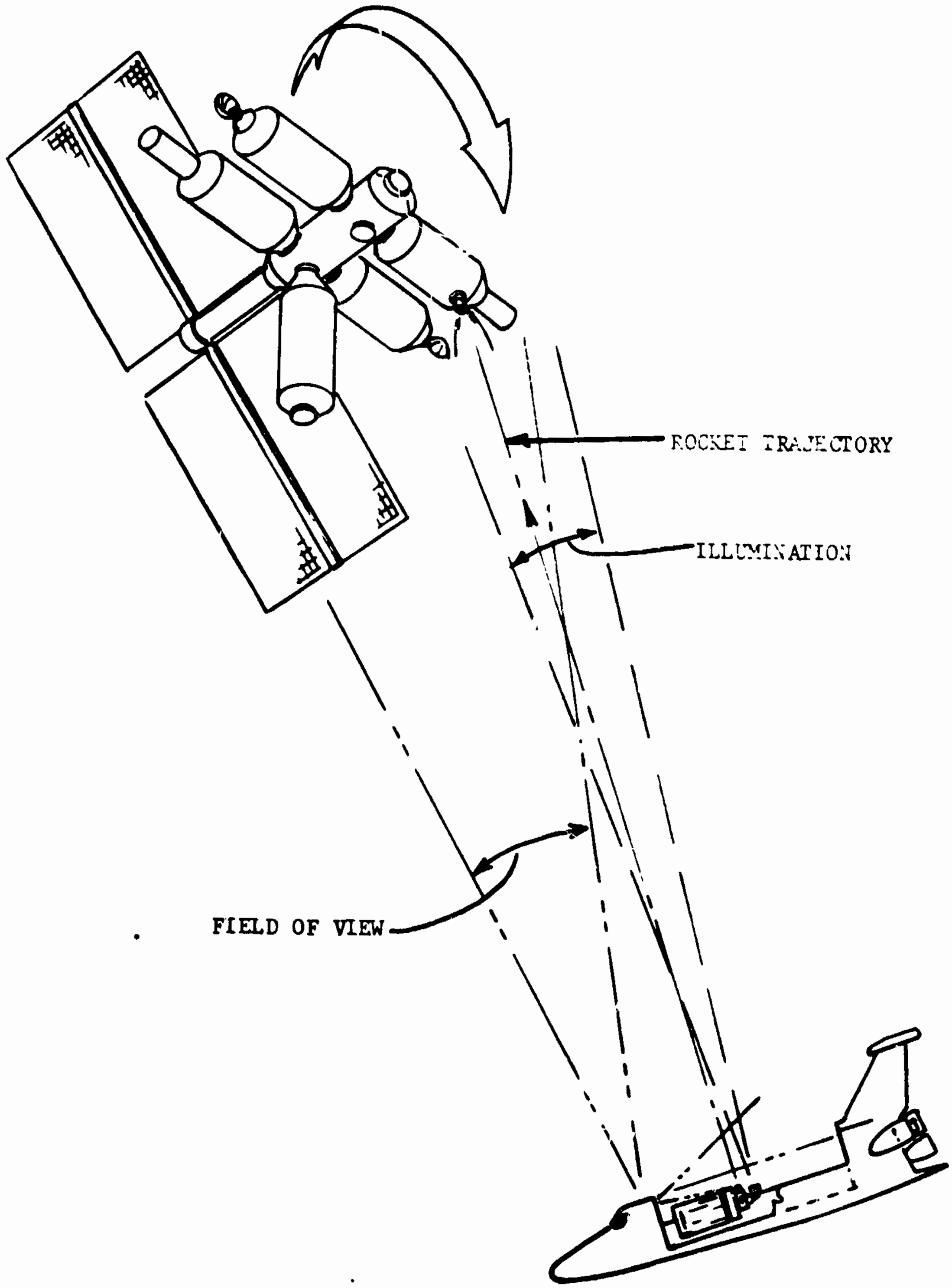


Figure 5-1B   Stick-On Rocket Concept used to Arrest a Tumbling Space Station

- Compared to the water stream concept, the stick-on rocket concept has a number of disadvantages. Because it contains propellants, it poses a hazard during storage, to the shuttle orbiter, and to the tumbling vehicle; it requires the development of some attach mechanism; and this mechanism could result in damage to the tumbling spacecraft.

The following recommendations are made, based on the objective of the task and on the above conclusions:

- Analysis and design studies of both the water stream and the stick-on rocket concepts should be continued, with the objective of confirming feasibility for both manned and unmanned tumbling spacecraft.

- If these studies confirm the feasibility and a reasonably low development cost, the more attractive of the two concepts should be developed and produced in a time frame to support the space shuttle program, and the devices held ready for potential use at the shuttle launch site(s).

- Effort on the other concepts should be discontinued at present, but be reviewed if the recommended concepts appear unattractive on further study.

5.1.2 Escape From a Tumbling Vehicle

The conclusions reached on personnel escape from a tumbling spacecraft are:

- Simple procedures are available for pressure-suited crewmen to abandon the four representative spacecraft examined in simple planar motion without interference or recontact with the structure. This may require pushing off by the crewmen with an impulse well within their capability. This conclusion is generally applicable within the range of tumbling rates considered.

- Multi-axis tumbling of the spacecraft should still allow ample margins for avoiding interference or recontact with the tumbling spacecraft.

- No appreciable reduction in crew performance is expected due to the tumbling motion at the worst angular rates considered (14.7rpm for the SSV). The ability of the crew to evaluate sensory cues as to the direction of spin motion in space cannot be determined from current data. Determining the correct direction in which to push off from the spacecraft into space may be difficult, however, particularly for the more severe tumbling cases.

- A number of relatively simple methods for reducing or arresting the tumbling of the individual crewmen after they have abandoned the spacecraft are possible. These allow the crewmen to be recovered by a standby rescue spacecraft. The two-man cable despin concept is the preferred one, with the extendable cable and the extendable rod despin concepts also being attractive potential concepts.

Recommendations made are as follows:

- The two-man cable despin and extendable cable despin concepts (Fig. 5-2 and 5-3) should tentatively be considered as the preferred modes for abandoning out-of-control manned spacecraft.

- The sources of tumbling, potential angular rates, and the feasibility of crew escape by the methods recommended should be re-evaluated at appropriate milestones in the development of the shuttle and other manned spacecraft.

- Research should be initiated into crewmen's ability to evaluate sensory cues in a tumbling spacecraft and while tumbling in space. The objective would be to determine if untrained personnel can make the decisions necessary for their safe escape and rescue.

5.2 TUMBLING CONDITIONS

5.2.1 Torque Producing Emergencies

Five potential sources of uncontrolled torque were considered in determining worst case tumbling conditions. These are:

- Collisions between two vehicles
- Escaping cabin atmosphere
- Escaping stored gas or fluid
- Hard-over gimballed engine
- Malfunctioning reaction control thruster

It is important to recognize that for some of the emergencies there is no clearly definable "worst case". This is so especially for collision, in which collisions at progressively larger velocities can be postulated; the limiting case is when catastrophic destruction of the vehicles occur. Similarly with hard-over gimballed engines and malfunctioning thrusters, enough propellants are carried on board, that rotational rates can result which would cause structural failure of the vehicles, and loss of personnel from the centrifugal forces. These situations were, therefore, limited by rational with arbitrary decisions as follows:

- Collision - 1.5 m/s (5 ft/sec)

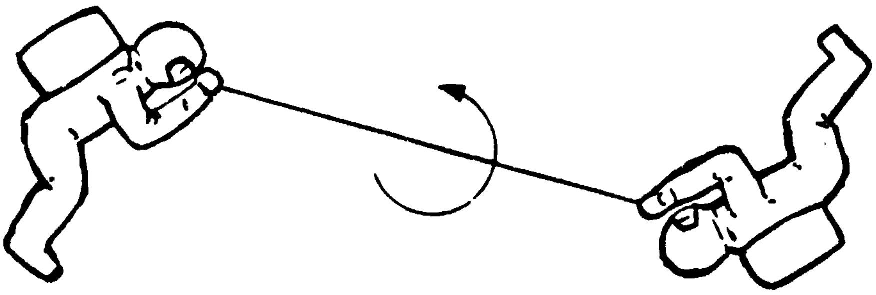


Figure 5-2. Two-Man Despin Device

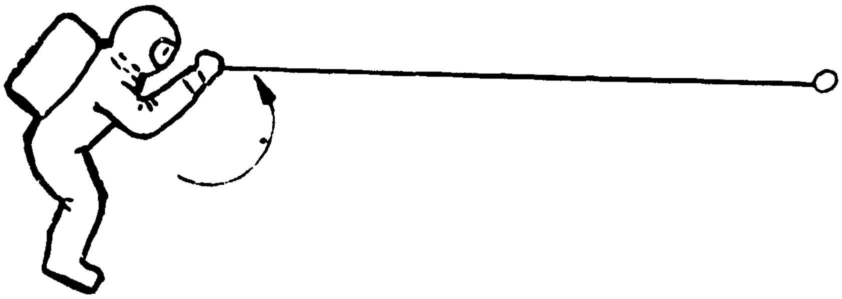


Figure 5-3. Extendable Cable Despin Device

. Hard-over gimballed engine - 15 seconds firing time

. Malfunctioning reaction control thruster - 60 seconds firing time

It is also assumed, as part of the emergency, that all attitude control or attitude rate control capability is lost following the buildup of angular rate.

5.2.2 Maximum Tumbling Rates

The maximum tumbling rates which can occur from the emergencies considered were determined in a study performed by Pennsylvania State University. This study was performed under NASA Grant NGR 39-009-210, and was based on mass property and other data supplied by NR/SD.

The results are summarized in Table 5-1.

The worst angular rate results from an escaping atmosphere on the small space vehicle. The maximum rate of 52 rpm produces an acceleration of over 20 g at the extremities of the vehicle, and would probably result in structural failure. This case is, therefore, not a case that could be survived if the leak occurred in the worst case condition as considered here.

5.3 ARRESTING TUMBLING BY EXTERNAL MEANS

This section identifies concepts for arresting the motions of tumbling spacecraft by means external to the tumbling spacecraft, and analyzes and evaluates these concepts.

5.3.1 Concepts for Arresting Tumbling

Twenty-three different concepts for arresting tumbling by external means have been identified. These are based on concepts developed at NR/SD on studies for despinning the ATS-V (unmanned) satellite by using a remote maneuvering unit, and on concepts identified specifically for this task. These are listed, illustrated, and briefly described in Table 5-2. The evaluation of these concepts is presented in succeeding sections.

5.3.2 Evaluation of Concepts for Arresting Tumbling

Evaluation of the candidate concepts was performed in three steps, reducing the number from 23 to 15, then to 5, and finally to the two selected concepts. The following set of evaluation criteria was postulated for use in the first screening of the concepts:

- Suitability for multi-axis tumbling
- Scheme complexity
- No dynamic interaction with manned rescue vehicle
- Compatibility with large configurations

The screening results are presented in Table 5-3.

Table 5-1. Summary of Maximum Tumbling Rates

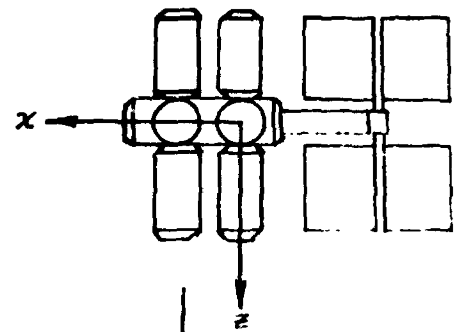
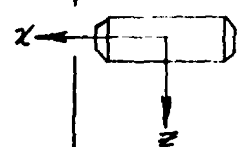
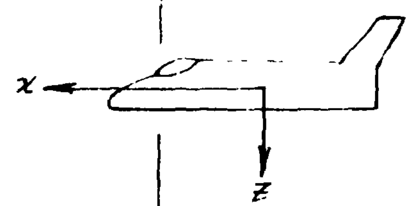
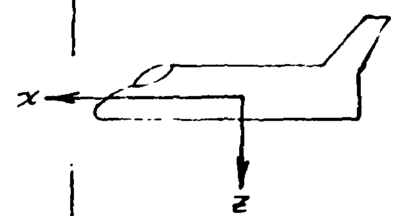
	Modular Space Station	Small Space Vehicle	Integral Tank Orbiter	Drop Tank Orbiter
				
Collisons	ω_X = 0.6 - 2.1 RPM	ω_Y = 4.7 - 14.7 RPM ω_Z = 4.7 - 14.7 RPM	ω_Y = 0.3 - 1.09 RPM	ω_Y = 0.5 - 1.45 RPM
Escaping Atmosphere	ω_Z = 8.9 RPM	ω_Y = 52 RPM ω_Z = 52 RPM	Not Critical	Not Critical
Escaping Gas or Fluids	0.4 - 4.0 RPM	Not Critical	Not Critical	Not Critical
Hard Over Gimbal	Does Not Apply	Does Not Apply	1 - 2 RPM	1 - 2 RPM
Malfunctioning Thruster	.03 RPM	ω_Y = 0.5 - 4.0 RPM	0.5 - 4.0 RPM	Not Critical

Table 5-2. Candidate Concepts for Arresting Tumbling

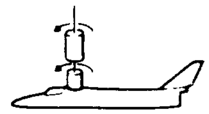
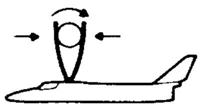
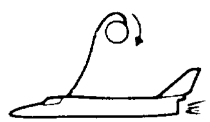
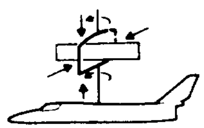
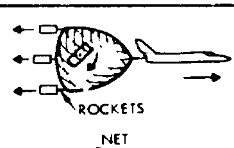
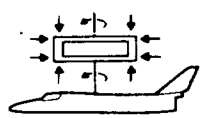
Number and Title		Description
1. Synchronous Docking Mechanism		Concept is similar to that proposed by NR/SD to despin the ATS-V satellite. Rescue vehicle employs rotatable docking ring which is spun up and synchronized to the tumbling vehicle angular rate, followed by mechanical docking and gradual arrest of tumbling vehicle.
2. Brake Band		A brake band is deployed around the tumbling vehicle. Arrest is controlled by variable braking pressure.
3. Harpoon		A rivet or other projectile is shot through a structural member of the tumbling vehicle on a long cable. The rescue vehicle accelerates momentarily, as the cable wraps around the tumbling vehicle to arrest the motion.
4. Synchronous Fork		A fork is synchronized to the angular rate of the tumbling vehicle and then deployed around it. Then, a pivot arm attached to the top of the fork would close to encircle the vehicle. The top and sides of the hoop would be collapsible to provide restraining forces to control precessional limits of the vehicle.
5. Towed Net		A net is deployed from the rescue vehicle with a set of rockets. The net wraps around the vehicle and the rescue vehicle accelerates to arrest motion. A variation would be a net attached to a hoop which would encircle the vehicle and subsequently arrest its motion.
6. Exhaust Plume Blast		Employs momentum from the exhaust plume of a rocket engine to arrest motion.
7. Synchronous Collapsible Basket		A basket with a net is spun up to synchronous speed with the top open. The basket is then placed over the tumbling vehicle and the top closed. The basket is collapsible, to control precessional rates.

Table 5-2. Candidate Concepts for Arresting Tumbling (Cont.)

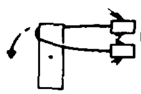
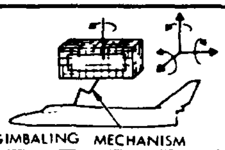
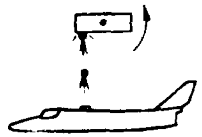
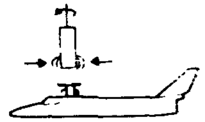
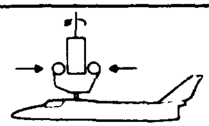
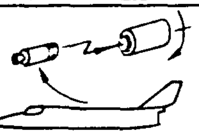
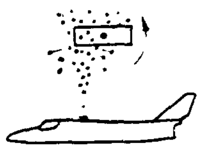
Number and Title		Description
8. Grappling Cable		A grappling cable with rockets at each end is deployed from the rescue vehicle. The rockets and cable straddle the tumbling vehicle above the center of rotation. When the cable contacts the vehicle, the rockets provide an arresting force. A cable catch on the vehicle keeps the cable attached on the half revolution in which it would normally be disengaged. The net torque over one cycle is in the direction to arrest the motion.
9. Gimballed Collapsible Basket		Similar to concept 7 except that collapsible basket is mounted on a 3-degree-of-freedom gimbaling mechanism. The synchronous feature is not required but could be employed to reduce overall basket dimensions.
10. Projectiles		Projectiles are shot to impact the tumbling vehicle and reduce its angular momentum.
11. Synchronous Clamping Mechanism		This concept is similar to Concept 1 except that mechanical jaws would be spun up to synchronous speed and then clamped around the vehicle to arrest the motion
12. Despin Mechanism with Inflatable Jaws		A flexible, inflatable material is deployed around the tumbling vehicle and then inflated until contact is made. Frictional forces are then controlled by metering inflation rates until the motion is arrested.
13. Water Stream		A mass medium such as water would be used to provide angular momentum. The water would be brought up in a shuttle and manually directed through a nozzle.
14. Remote Controlled Tug		Remote controlled tug containing sensors and propulsion attaches itself and then arrests the motion using reaction control. Remote control from shuttle using TV.
15. Cloud of Balls		Use the shuttle - several flights if necessary - to place a "cloud" of objects around the tumbling vehicle. As the objects collide with the vehicle it will gradually slow down.

Table 5-2. Candidate Concepts for Arresting Tumbling (Cont.)

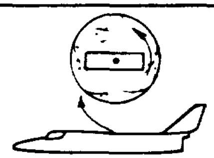
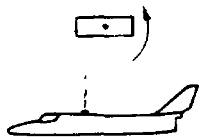
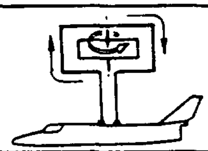
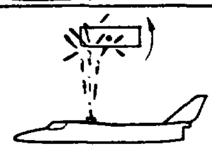
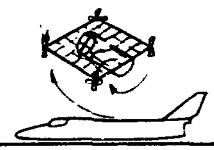
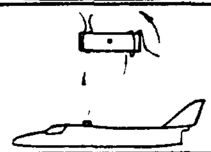
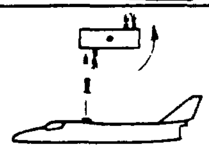
Number and Title		Description
16. Gas Bag		Place a bag around the vehicle, close it and then pressurize it. Slowdown occurs through windage losses.
17. Gas Stream		A gas stream is directed against the tumbling vehicle similar to Concept 13.
18. Induced Eddy Currents		Deploy large current loops around the vehicle - eddy currents will form in the vehicle skin and structure and act as drag to arrest the motion.
19. Foam		Place a field of foam around the vehicle. Portion that sticks will increase the inertia and decrease the rate. Portion that impacts will act as high-density fluid inducing drag.
20. Energy Absorbing Net		A net is remotely controlled from the shuttle. Net engulfs the tumbling vehicle and energy is absorbed in the net - breaking strands or working strands. RCS removes momentum.
21. Rope Projectiles		Shoot flexible ropes onto the tumbling vehicle. Energy dissipation occurs through flexure or working of the ropes. Tumble is converted to pure spin about the major inertia axis. Ropes also increase inertia and thereby reduce rates.
22. Net and Rods		A large net is placed over the tumbling vehicle. Net has large rods with tip masses that increase inertia and lower spin rate.
23. Stick-On Rockets		Projectiles are shot from the shuttle. Upon impact with the tumbling vehicle a rocket ignites and reduces the angular rate. Probably use several relatively small units

Table 5-3. Evaluation of Concepts for Arresting Tumbling

Concept No.	Title	Evaluation Criteria: Multi-Axis Tumbling	Scheme Complexity	Interaction with Rescuer	Compatibility	Selection for Further Study	Remarks
1	Synchronous Docking Mechanism	X	X	X	X	-	Requires prepared passive damper, needs docking ring on c.g. along principal axis
2	Brake Band	X	X	X	X	-	Needs passive damper, does not need docking ring
3	Harpoon	✓	X	XX	✓	-	Requires special structural provisions to withstand local loads, analysis will be difficult
4	Synchronous Fork	X	X	X	X	-	Needs passive damper, may physical damage vehicle
5	Towed Net	✓	X	X	✓	✓	Better to use unmanned tug
6	Exhaust Plume Blast	✓	X	✓	✓	✓	Coarse corrections, structural damage from blast, requires frequent repositioning of rescue vehicle, not suitable for roll on SSV
7	Synchronous Collapsible Basket	✓	X	X	X	-	Probably physical damage to vehicle
8	Grappling Cable	X	X	✓	✓	-	Localized structural damage from concentrated load application, requires G&C for propulsion packages, not suitable for roll on SSV
9	Gimballed Collapsible Basket	✓	XX	X	X	-	Gimbal complexity is high and benefits uncertain
10	Projectiles	✓	✓	✓	✓	✓	Potential structural damage
11	Synchronous Clamping Mechanism	X	X	X	X	-	Needs passive damper, structural damage, no docking ring required
12	Despin Mechanism with Inflatable Jaws	X	X	X	X	✓	Probably less structural damage than 11, best of grasping types
13	Water Stream	✓	✓	✓	✓	✓	Coarse corrections, inefficient

Table 5-3. Evaluation of Concepts for Arresting Tumbling (continued)

Concept No.	Title	Evaluation Criteria: Multi-Axis Tumbling	Scheme Complexity	Interaction with Rescuer	Compatibility	Selected for Further Study	Remarks
14	Remote Controlled Tug	✓	X	✓	✓	✓	--
15	Cloud of Balls	✓	✓	✓	✓	✓	Space junk residue, not suitable for roll on SSV
16	Gas Bag	✓	X	✓	X	✓	Bag deployment and closure complexity; collisions between vehicle and bag
17	Gas Stream	✓	✓	✓	✓	✓	Gas stream dispersal, not suitable for roll on SSV
18	Induced Eddy Currents	✓	X	✓	✓	✓	--
19	Foam	✓	✓	✓	✓	✓	Visibility problems in approaching vehicle after despin
20	Remote Controlled Net	✓	✓	X	✓	✓	--
21	Rope Projectiles	✓	✓	✓	✓	✓	--
22	Net and Rods	✓	X	✓	✓	✓	Potential structural damage
23	Stick-On Rockets	✓	✓	✓	✓	✓	--

LEGEND:
✓ Means satisfactory or unknown
X Means poor
XX Means unacceptable

The fifteen concepts which survived this initial screening were considered for further study. In the second step of the evaluation a preliminary sizing analysis of the 15 concepts resulted in rejection of 10 of the concepts. The rejected concepts and the rationale for their rejection are listed in Table 5-4.

Table 5- 4. Rationale for Rejection of Concepts for Arresting Tumbling

Concept	Reason for Rejection
. Towed net	Complex, non-analyzable
. Exhaust plume blast	Operationally impractical
. Projectiles	Limited Applicability
. Cloud of balls	Low efficiency, space debris left in orbit
. Gas bag	Container development, operational complexity, potential damage to gas bag or tumbling vehicle
. Gas stream	Low efficiency, high weight penalty
. Eddy current damping	Excessive power requirements (hundred of kilowatts)
. Foam	Operationally impractical
. Rope projectiles	Excessive weight
. Nets and rods	Excessive weight, questionable feasibility

The remaining 5 concepts are:

- Despin mechanism
- Water stream
- Remotely controlled tug
- Remotely controlled net
- Stick-on rockets

Some salient features of these five concepts are compared in Table 5-5.

In the final screening, the following selection criteria were applied to the five potentially acceptable concepts to arrive at those recommended.

- The preferred concept must involve low investment costs (i.e., development and manufacturing costs before use), since large funding levels are unlikely to be made available for such contingency devices.
- Operating costs must be reasonable
- The device, once developed and built, must be available for operations at very short notice (hours to one day, consistent with a shuttle emergency flight).

Table 5-5. Comparison of Five Concepts for Arresting Tumbling

Parameter	Concept				
	Remotely Controlled Net	Water Stream	Stick On Rocket	Remotely Controlled Tug	Despin Mechanism With Inflatable Jaws
Application	Space Station Shuttle Orbiters Small Space Veh.	Space Station Shuttle Orbiters Small Space Veh.	Space Station Shuttle Orbiters Small Space Veh.	Space Station Shuttle Orbiters Small Space Veh.	Small Space Vehicle Only
Weight, KG (lb)	560 - 3200 (1250 - 7000)	800 - 8600 (1800 - 19000)	30 - 320 (70 - 700)	225 - 9000 (500 - 20000)	450 - 1350 (1000 - 3000)
Spacecraft Damage	Minor Damage to Weak Appendages	Minor Damage to Weak Appendages	Possible Inadvertant Damage to Weak Appendages.	Minor Damage	Minor Damage
Major Elements	Deployable Frame Propulsion Electronics Simulation	Pumps Fluid Dynamics Simulation	Propulsion Attach Method Gun Launcher Simulation	Propulsion Electronics Attach Method Simulation	Despin Mechanism Inflat. Bag Simulation
Development Risk Areas	Deployment System	Fluid Dynamics (Efficiency)	Attach Method	Attach Method	Despin Mechanism

- The device should be able to deal with a wide range of tumbling vehicle size and configuration (including, if possible, the many unmanned vehicles expected in orbit), and of angular rates.

- It should be capable of being operated with a minimum of training and simulation, and preferably not require a specialized crew.

- There should be good confidence that the system will be effective, with adequate margin for miscalculations, errors, and special contingencies.

The concept that is judged to best satisfy these criteria is the preferred concept. The evaluation of the five concepts according to the above evaluation criteria is ultimately a matter of judgment. The judgment used is documented in Table 5-6.

Table 5-6. Evaluation of Five Concepts

Criteria	Despin Mech with Inflatable Jaws	Water Stream	Remotely Controlled Tug	Remotely Controlled Net	Stick-On Rockets
Low investment cost	Moderate*	Excellent	Moderate*	Moderate	Good
Reasonable operating costs	Moderate	Good	Moderate	Good	Good
Operationally available at short notice	Moderate	Excellent	Moderate	Moderate	Excellent
Wide range of applicability	Poor**	Good	Moderate	Good	Good
Minimum crew training	Moderate	Good	Moderate	Excellent	Good
Good confidence with adequate margins	Moderate	Good	Moderate	Moderate	Good
Minimum damage to tumbling vehicle	Moderate	Good	Moderate	Moderate	Moderate

* Assume existence of developed tug, mini-tug, or remote maneuvering unit

** Not suitable for large vehicles

Some of the rationale for these judgements are presented below.

- The despin mechanism, remotely controlled tug, and remotely controlled net require development of fairly complex mechanisms and/or propulsion systems. The stick-on rockets can use existing rocket motors, but the attach mechanism requires developing and testing. The water stream concept can basically use off-the-shelf components, but requires analysis, development and testing of the nozzle. In addition, as shown by the asterisks in the table, the despin mechanism, and the remotely controlled tug are feasible only if a tug, mini-tug, or remote maneuvering unit have already been developed and are available.

- The operating costs of each concept are basically the costs of one emergency shuttle flight. Additional costs, such as special checkout and ground support, are small relative to the shuttle costs. The remotely controlled tug, however, does involve the flight f some kind of tug, which significantly increases operational costs.

- The water stream concept can be taken on-board as a shuttle payload with very little preparation, and requires only filling of the water tank. Similarly, the stick-on rocket concept requires only flight preparation of the solid rocket motors. The other three concepts, however, involve liquid propellant systems, which require some time for loading and checking out. This may, indeed, be the limiting factor in launching the shuttle with these concepts.

- The despin mechanism is capable of use on the small space vehicle only, or small unmanned satellites. It is not applicable to large vehicles, such as the orbiter or space station.

- The water stream and stick-on rocket concepts are relatively simple to operate and, because they are incremental in their application, a large degree of trial and error during use can be tolerated. Practice on a simulator may even show that the water stream may be operated intuitively (providing visibility and illumination are adequate). Intermittent use would allow pauses for evaluation of results. Similar simplicity of operation may be possible with the stick-on rocket concept. The remotely controlled net may also be very simple to operate, requiring only control of the net trajectory to intercept the target. The other systems appear to require much more training and practice, however, and would almost certainly require a specially-trained crew, with considerable experience on a simulator.

- The water stream and stick-on rocket concepts, because of their simple reliance on basic momentum transfer principles, provide the best confidence that they can successfully arrest the tumbling spacecraft. Their incremental use, again, adds to the confidence, since considerable errors in use can be tolerated. The other three concepts are more complex, and must basically operate the first time. All concepts can be sized so that they have a margin of at least two or three times to allow for errors.

- The water stream concept should result in mininal damage since very low impingement pressure are experienced on the tumbling vehicle. The other concepts can result in damage, particularly to appendages. The stick-on rockets may require penetration of the structure to operate successfully.

5.4 DESCRIPTION OF RECOMMENDED CONCEPTS

5.4.1 Water Stream Concept

The rescue vehicle contains a water tank, pump, and a remotely controlled nozzle. The jet of water is directed by positioning and orienting the rescue vehicle so that the water stream impinges on the tumbling vehicle so as to reduce its angular momentum. As the stream will be visible and will move in a straight line, the operator can easily adjust the rescuing vehicle orientation so that the stream impacts the tumbling vehicle at the desired point. The water can be applied in bursts to maximize efficiency and to allow evaluation of the results in real time. The reaction of the water jet on the rescuing vehicle can be counteracted by the attitude control system.

A practical working range for the water jet velocity is of the order of 30 to 120 m/s (100 to 400 fps) with corresponding pump pressures in the range of 5×10^5 to 8×10^6 N/m^2 (70 to 1100 psi). Nozzle thrusts should be in the range of 50 to 500 N (10 to 100 lb) with nozzle area within the range of 0.05 cm^2 to 10 cm^2 (0.01 to 1.5 $in.^2$). As the fluid stream will travel a fairly long distance before impact--perhaps 60 m (200 ft)--the impact area will be significantly expanded from the nozzle area. As a matter of fact it is desirable that the stream cross section expand to spread the load over a large area and reduce the effective impact pressure. Pressures of 5 to 500 N/m^2 (0.1 to 10 psf) and impingement areas in the 1 to 10 m^2 (10 to 100 ft^2) range are practical. The fluid tank will have a volume on the order of 15 m^3 (500 ft^3).

An estimate of the weight of water required is shown in Table 5-7, assuming an application efficiency of 50 percent and a stream velocity of 122 m/s (400 fps). It is estimated that the tankage, plumbing, pumps, and other equipment could be provided for another 1350 kg (3000 lb).

The total energy required, assuming a stream velocity on the order of 120 m/s is within the present support capability of the shuttle (less than 50 kwhr). Peak power on the other hand represents a potential limitation on this concept. The present orbiter power transfer capability is in the 1 to 10 kw range. The system may require a special power supply for the move severe cases.

Table 5-7. Weight of Water Required to Arrest Worst Case Tumbling

Configuration	Weight of Water Required kg (lb)	
Integral tank orbiter	6500	(14,400)
Drop tank orbiter	1970	(4,350)
Modular space station	7270	(16,100)
Small space vehicle	676	(1,490)

Since only low impingement pressures are experienced, no damage to the tumbling vehicle is anticipated. A finely atomized stream appears desirable to minimize high localized impingement pressures; local impingement pressures vary inversely as the drop diameter. This still applies even if the drops are frozen.

Since the water expands to a vacuum, some evaporation may be expected, and the remainder of the water will turn into ice. The lower the initial temperature of the water, the less the amount of evaporation. For a water near to the freezing point, approximately 14 percent will evaporate at a maximum. This gas stream will still be directional, however, and will contribute to the momentum transfer if it impinges.

Reaction propellant requirements to counteract the nozzle thrust of the rescuing vehicle are small and within normal capacities. An attractive feature of the concept is that the working fluid is clean in terms of the residue left in orbit.

Details of the water stream kit installed in the rescuing orbiter are shown in Figure 5-4. The kit consists of a water tank, a motor/pump/nozzle assembly, a pressurizing gas bottle, a floodlight, a battery pack and associated controls, and a payload retention consisting of a simple welded structure. Since the whole kit is well within the orbiter's payload capacity, all components are designed like ground equipment rather than spacecraft equipment. Standard materials and large factors of safety can be used to reduce costs and testing. The water tank is spherical, about 2.8 m (9 ft) diameter and made of steel. It contains a rubber bladder for positive expulsion of water. This is pressurized to 14000 N/m^2 (20 psi) from the high pressure (21 x 10^6 N/m^2, 3100 psi) nitrogen tank. The water pump is an axial flow swash-plate piston type, which allows for a large range of flow rate and pressure. This is driven by a variable speed 10 kw dc electric motor with solid-state control. The motor is water jacketed and is cooled by the water flowing through the jacket as it is being pumped through the nozzle. The whole of the motor and pump is enclosed in a pressurized 1 atmosphere air or nitrogen environment to avoid design and qualification for a vacuum environment. The tanks and the motor and pump are insulated for thermal protection. The whole kit is supported in the orbiter cargo bay by a 5-point attach system, which fits into the standard cargo bay attach points.

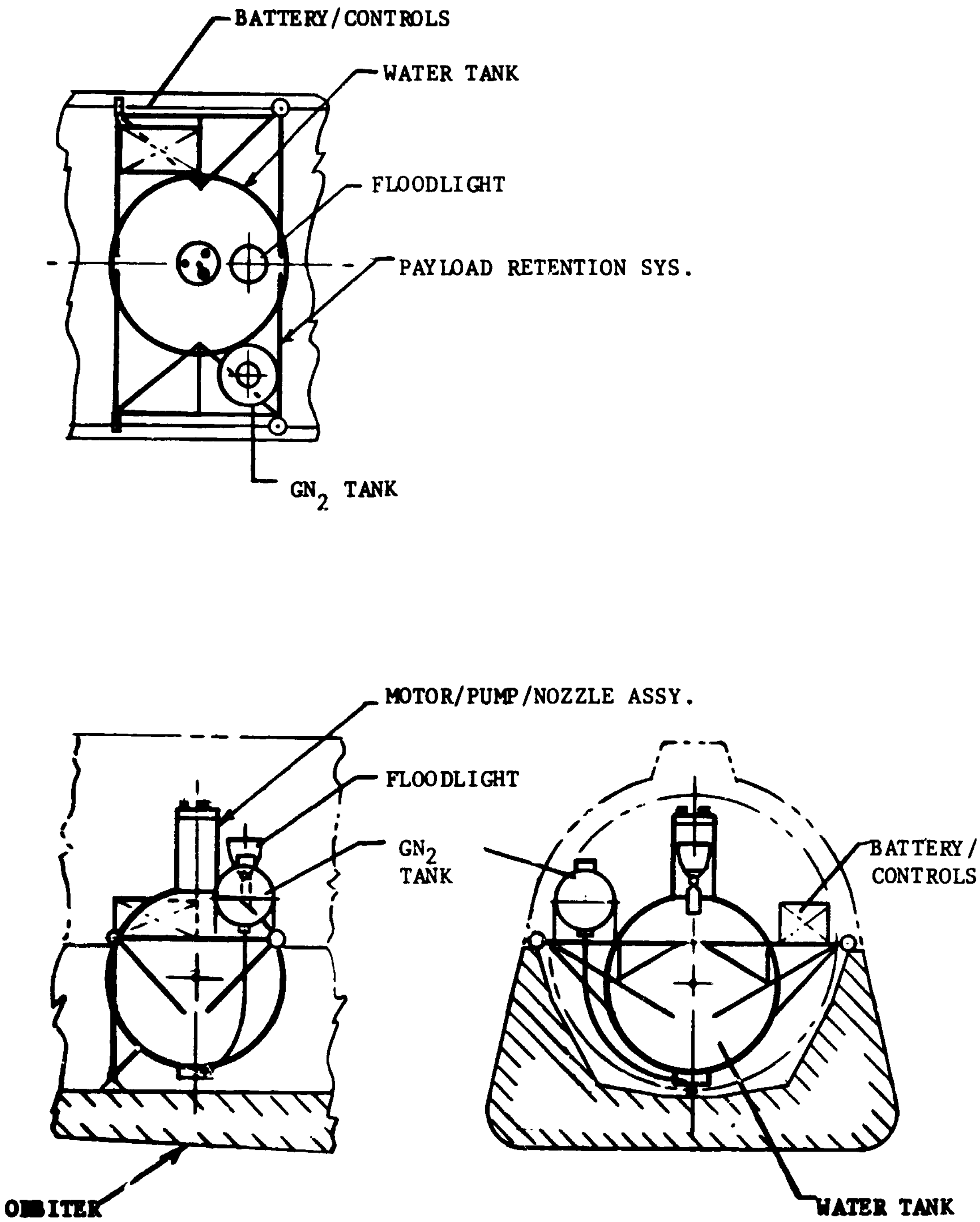


Figure 5-4. Water Stream Kit

If more water is required than can be accommodated in one kit, two kits may be loaded in the cargo bay.

5.4.2 Stick-On Rocket Concept

Small solid rockets are "shot" from a "gun" on the orbiter at low velocity toward the tumbling spacecraft. These do not have any onboard guidance and are spin stabilized. They attach themselves on impact, which initiates ignition of the single nozzle engine (thrusting toward the attach point). Many rockets are required to accomplish despin. Visual cues and simple computer functions are required to determine tumbling rate and rocket launch time. Rc kets require variable timers and possibly thrust termination capability to bring the tumble rate to near zero; or they can be sized small enough to produce the desired fine control.

Individual rockets which may unintentionally attach on the wrong side of the center of gravity, or which become badly deflected after attach, would add to the momentum instead of reducing it. For this reason a lot of small rockets are preferred, with visual feedback of where they hit.

The rockets were sized to remove all the spacecraft tumbling rate specified in Table 5-1. The effect of impact provides an additional, though small, despin impulse. Half the weight of the module was assumed to be propellant. Modules are envisioned to be solid propellant engines weighing approximately 10 to 20 kg (20 to 40 lb) each. Weights of the modules presented in Table 5-8 show that a propulsive means of removing angular rates is an order of magnitude more efficient than any other means.

Table 5-8. Weights and Number of Stick-On Rockets to Arrest Worst Case Tumbling

	Vehicle			
	Integral Tank Orbiter	Drop Tank Orbiter	Modular Space Station	Small Space Vehicle
Total module weight, kg (lb)	277 (610)	75 (165)	304 (670)	32 (70)
Approximate number of modules required	14 - 28	4 - 8	15 - 31	2 - 4

A single size stick-on rocket is applicable to the multiaxis tumbling of a wide range of configurations (except possibly for the roll axis of a symmetric configuration) and has the lowest weight of any concept. No dynamic interaction between the tumbling spacecraft and rescue vehicle is inherent in this concept. Although recognition of body rates from inertial motion observation may be

difficult, it is felt that the difficulty can be overcome with ground simulation and training. Adequate visual cues exist for aiming and launch timing but could be supplemented by simulation and training.

The major potential technical development problem is development of the attach mechanism. In the concept shown in Figure 5-5, the flat plate has a serrated surface on a pneumatic pad. This spreads the contact load over its whole area (to avoid damage to the spacecraft surface) and also provides a lot of friction to prevent sliding over the surface. A protruding trigger initiates firing of the rocket motor immediately upon contact, and the rocket thrust, combined with the friction of the pad, maintains the initial orientation of the rocket against the spacecraft surface.

The rocket is spin-stabilized at about 5 rpm in its trajectory toward the tumbling spacecraft. (This is a low enough rate that it does not pose any problems for attachment). The shape shown for the rocket is designed for good dynamic stability in flight, at contact, and during firing. The surface contacted may vary by as much as 20 degrees from the normal to the flight path of the rocket with very little loss in effectiveness in reducing the angular momentum. At larger angles, of around 45 degrees, the friction may initially be insufficient to hold the rocket firm, and it may settle at an angle that introduces unwanted components in momentum. Since a large number of rockets will be required to stop the tumbling, however, it is only necessary that they are correctly oriented on the average. If an occasional rocket makes contact on the wrong side of the center of gravity, or misses altogether, the effect can be corrected by subsequent rockets. Because of their high specific impulse these rockets are very efficient in terms of weight and a much greater supply than the theoretically required minimum can be carried on a given mission.

Rockets which miss the spacecraft will be fired by a timer to reduce the hazard of collision with a spacecraft at a later time.

When the rockets are spent the friction force will vanish and the empty motors will each take up an independent trajectory, away from the spacecraft. These spent rockets thus become space debris, and a hazard to other spacecraft.

An alternative rocket design which avoids this problem is shown in Figure 5-6. In this concept the front plate is mounted on a ball joint, so that the plate can adjust itself to the surface of the spacecraft immediately upon contact. When a trigger in the center of the plate makes contact with the spacecraft, three things happen simultaneously. First, a number of spring-loaded pins are shot out from the plate, penetrating the contact surface, and latches in the pins lock the plate against the surface. Secondly, the ball joint is locked by a friction device so that the rocket retains its flight path orientation relativel to the spacecraft surface, irrespective of the surface angle. Thirdly, the rocket motor firing is initiated. A timer is again provided to fire rockets which miss the spacecraft.

Details of the installation of the rockets in the rescue orbiter cargo bay are shown in Figure 5-7. The individual rockets are stored in a magazine, and are fed one at a time into a launching device. This is electrically operated, and controlled by the rescue orbiter crew. The rockets are propelled by springs or pneumatically along a guide rail, which also imparts the spin.

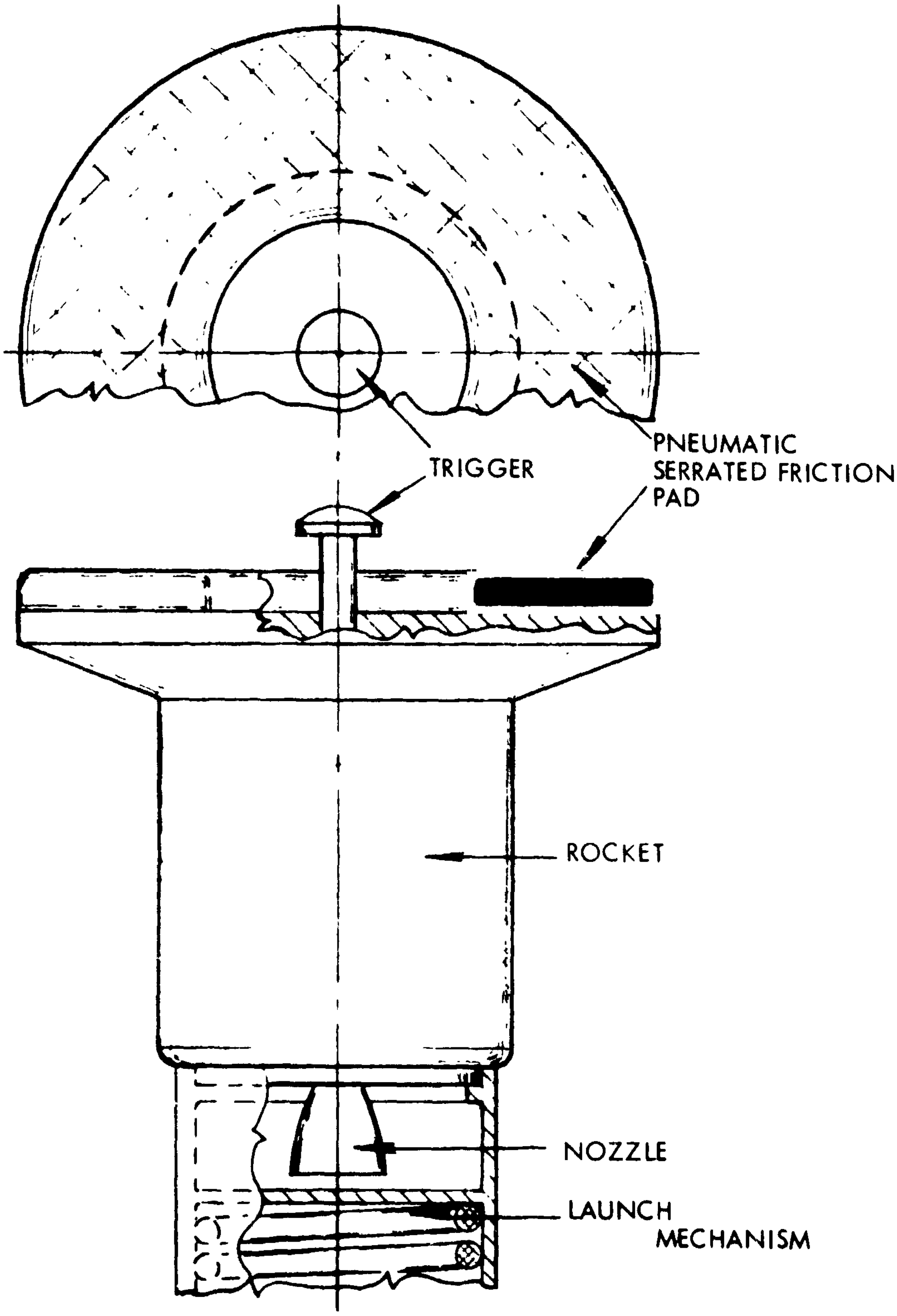


Figure 5-5. Stick-On Rockets with Pneumatic Pad

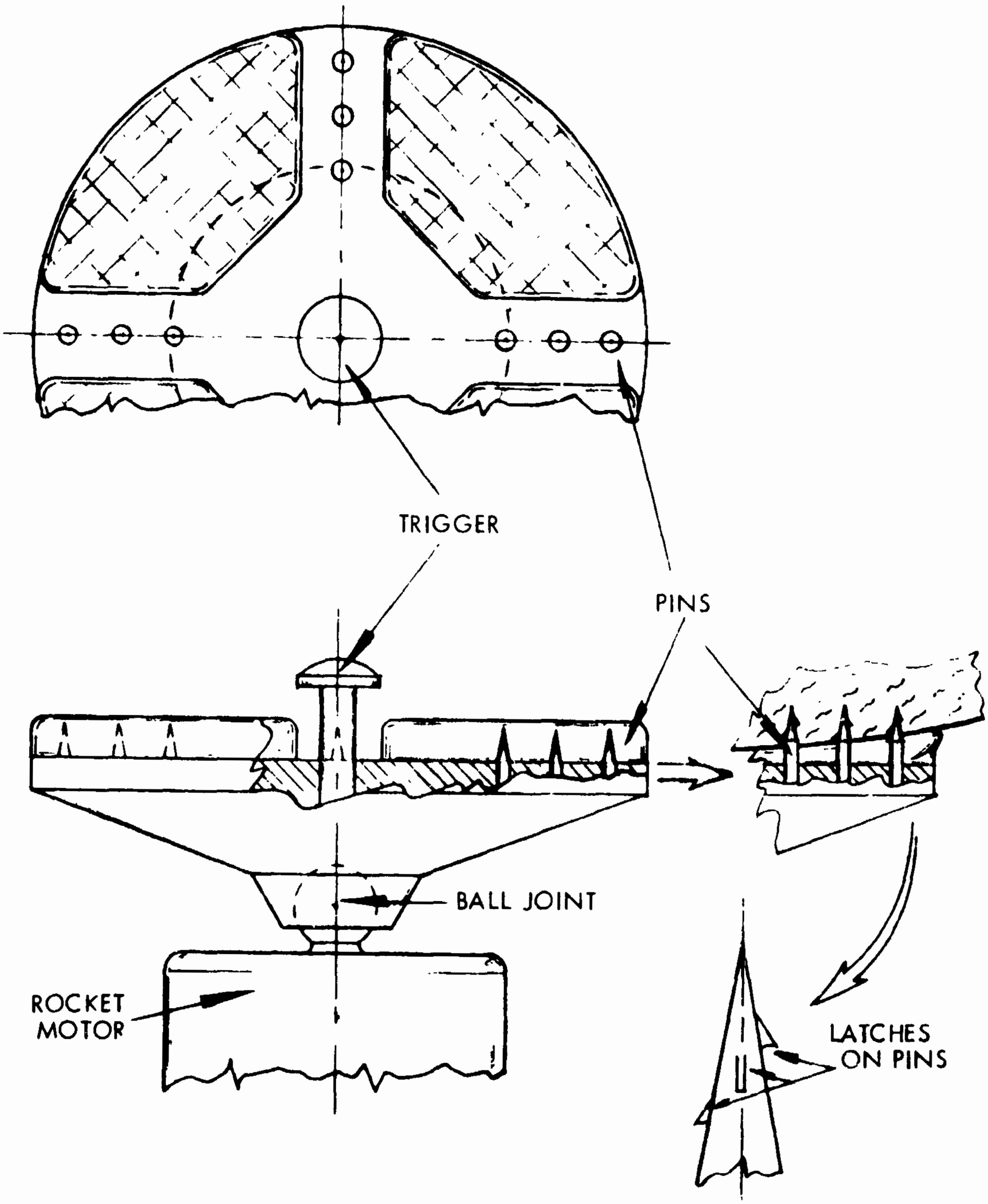


Figure 5 6   Stick-On Rocket with Positive Attach Mechanism

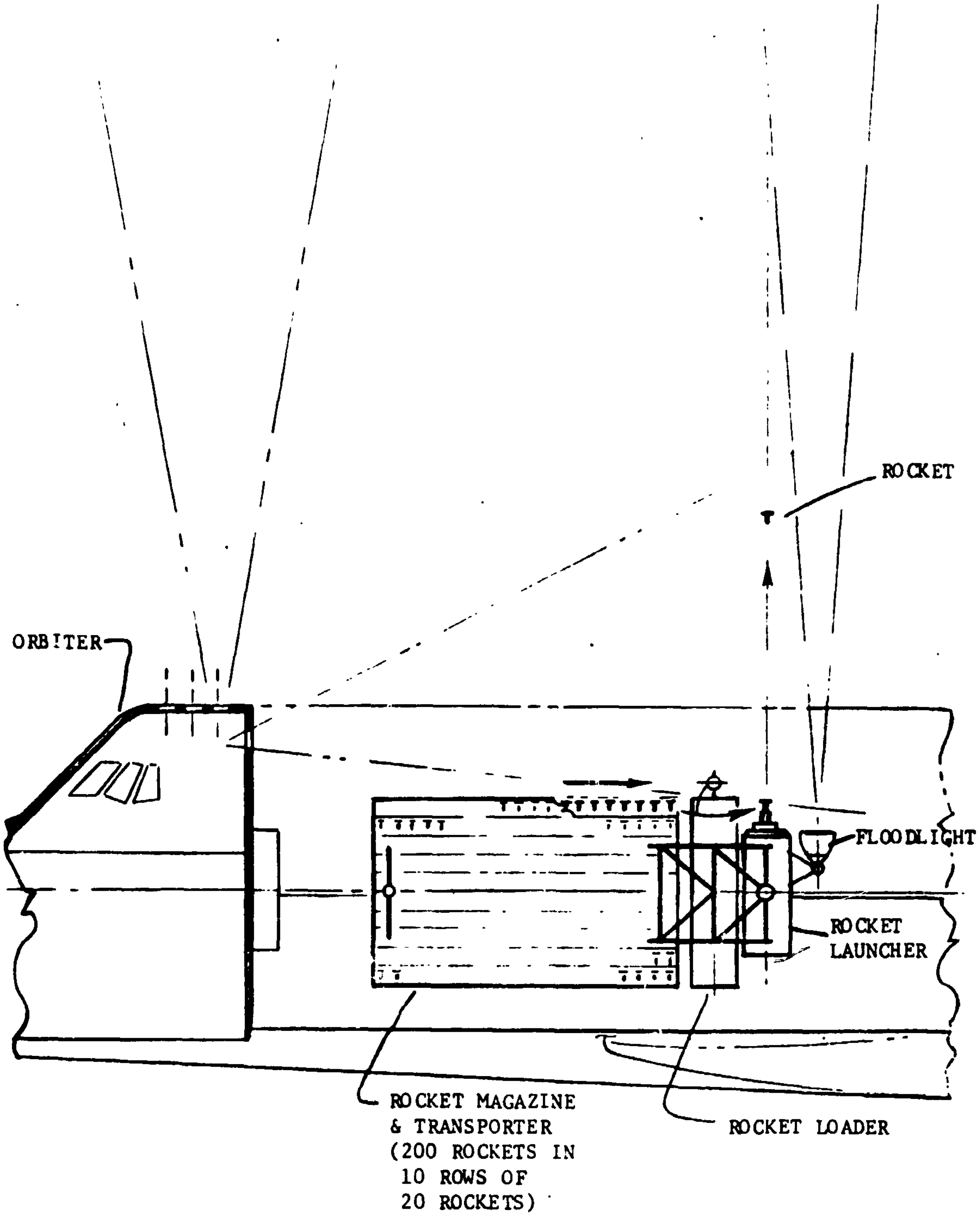


Figure 5-7. Stick-On Rocket Kit in Orbiter Cargo Bay

5.5 ESCAPE FROM A TUMBLING VEHICLE

This part of the study was directed toward the dynamics aspects of retrieving the crew from a disabled, tumbling spacecraft. It is assumed that a rescue vehicle cannot dock with the distressed craft and due to the tumbling motion the rescue vehicle must stationkeep at some safe distance. It is, therefore, necessary to somehow move the crew of the disabled vehicle far enough away that they can be retrieved without the danger of a collision between the tumbling vehicle and the rescue vehicle. It is furthermore assumed that the disabled spacecraft does not include any type of escape vehicle. Thus the study is restricted to consideration of the case where crewmen leave the vehicle in pressure suits with individual life support backpacks. Once safely away from the tumbling craft, the crewmen are picked up by the orbiter, perhaps with the aid of a manipulator.

5.5.1 Crew Capability

The crewman upon leaving the tumbling spacecraft will have the angular rate of the spacecraft and a linear velocity relative to the spacecraft equal to the instantaneous velocity of that part of the spacecraft relative to its center of gravity at the instant of separation. In addition, he will have superimposed whatever motion he is capable of imparting to himself by physically pushing off against the spacecraft.

The crewman is able to provide a relative separation velocity between himself and the spacecraft by pushing off when leaving. An estimate of this velocity is made based upon man's ability to jump. On earth the 50 to 95 percentile man in good physical condition can raise his center of gravity 0.3 m (1 ft). In zero g this is equivalent to pushing off with an initial velocity of 2.5 m/s (8.0 fps). As an escaping crewman he will be encumbered with a space suit and a portable life support system (PLSS), and his separation velocity is between 1.7 and 1.8 m/s (5.5 to 5.9 fps) for the 50 and 90 percentile man respectively.

The escaping crewman is capable of changing his tumbling rates by changing his inertia or by motion of his extremeties. He is capable of little, if any, damping without additional equipment. If the crew could leave the tumbling spacecraft at 14.7 rpm (for the SSV) in a crouched position (which would be very awkward), the best he could to by extending his extremeties would be to reduce his tumbling rate to approximately 5 rpm. Continual motions of the arms could reduce the crewman's head and trunk angular rates; however, termination of the motion would restore the initial tumbling rates. Supplementary equipment is thus required to reduce the tumbling rates further and if possible permanently.

5.5.2 Configuration Evaluation

The analysis of the mechanics of escape from complex configurations such as are involved here is extremely complex for the general case of multi-axis tumbling because of the complex geometries involved. As a first approach, therefore, the capability of the crew to escape from the tumbling vehicles as they are instantaneously rotating about each of their principal geometric axes was analyzed. It is felt that since sufficient separation velocity margins

exist for these representative cases, there is nothing inherent in multi-axis tumbling that would significantly increase those separation velocity requirements.

Each of the four configurations is analyzed separately in what follows. These analyses show that the crewmen can escape without recontact or interference within the structure either by just stepping off, or with a slight push-off well within tne normal physiological capability, assuming that they can make the necessary judgments.

A. Integral Tank Orbiter

The worst case initial condition was assumed to be a yaw rate of 4 rpm. All exits were assumed to occur from the hatch located on the upper surface of the fuselage behind the cockpit. Leaving from this point with no additional velocity and the nominal center of mass location, the crewman easily clears the tail fin. The center of mass could be 12 m (40 ft) further forward and the natural tangential velocity would be adequate for safe escape.

In the case of pitch motions, the procedure is a function of the direction of spin. For a negative pitch motion, the crewman simply steps off and the tangential velocity provides adequate clearance with the tail. For positive pitch motions, the crewman climbs out and pushes slightly in the Y axis direction. The object is to slide over the side of the fuselage. Once clear of the fueselage, the tangential velocity will provide adequate aft fuselage clearance.

For roll motions of the vehicle, the crewman exists at the same point but pushes away along the Z axis.

B. Drop Tank Orbiter

The drop tank orbiter configuration was analyzed assuming a spin about the yaw axis at a rate of 2 rpm. A sketch of the configuration is shown in Figure 5-8. For this vehicle the crew would escape from the docking port shown in the sketch.

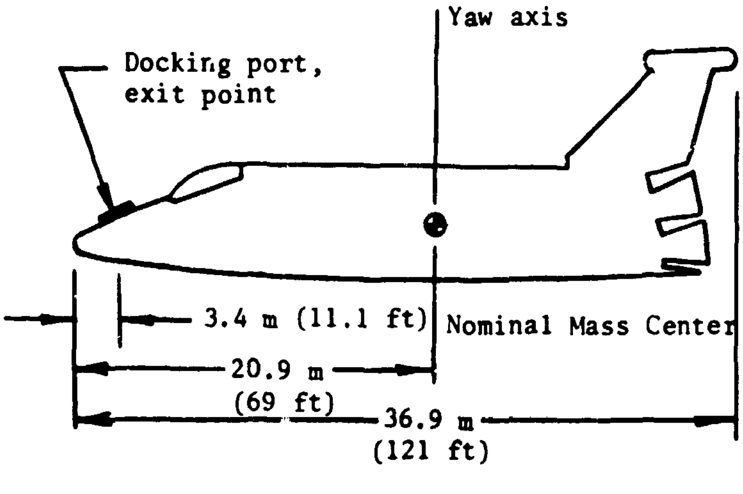


Figure 5-8. Drop Tank Orbiter Configuration

For nominal, orbital center of mass locations, no additional velocity is required. The tangential velocity associated with the spin is adequate to safely clear the vehicle. The mass center could be 8 m (26 ft) further forward before the tangential velocity alone was not sufficient to properly clear the vehicle. With a mass center approximately 13 m (42 ft) forward of nominal, an additional velocity of 0.14 m/sec (4.6 fps) would be required. This is well within a man's push-off capability.

For a negative pitch rate the crewman simply "steps off" and the analysis presented above for yaw motion is applicable. Tangential velocity alone is sufficient to clear the tail. For a positive pitch rate, the crewman should plush slightly in the plus or minus Y direction such that he will slide along the nose of the vehicle. Collision with the aft fuselage will not occur as the relative motion computed for the yaw case is essentially applicable.

For rolling motion of the orbiter, the crewman would exit at the same point but push to provide a velocity toward the nose of the vehicle.

It appears from this analysis that escape from the drop tank orbiter can be accomplished with no more than a simple push-off to obtain the required velocity.

C. Modular Space Station

For the specific cases of single axis motion about each of the body axes, it was determined that crew escape can be accomplished using the natural tangential velocity of the vehicle. In some cases a slight push-off is advantageous. The solar arrays can be positioned to facilitate escape. Although the case of a random tumble was not analyzed, it is believed that a more detailed analysis would show that escape can be accomplished safely.

D. Small Space Vehicle (SSV)

The most critical case for this vehicle is the case where the vehicle has a single port near the mass center. It is necessary to evaluate the relative velocity required to prevent a collision. The analysis is valid for the vehicle spinning about either the Y or Z axis. Velocity addition in the tangential direction is more efficient than in the radial direction. A representative sketch is shown in Figure 5-9. This sketch illustrates the escape process, including the path of the crewman, and the critical point the crewman has to clear to avoid a collision.

The results of the analysis are presented in Figure 5-10. The plot shows the additional velocity required as a function of the distance between the escape port and the vehicle center of mass assuming a total vehicle length of 11.3 m (37 ft). Two tumble rates are shown. Safe escape occurs without velocity addition as long as the vehicle mass center is more than about 2 m (6.5 ft) from the escape port. Assuming a crewman can push off and obtain a relative velocity on the order of 1.8 m/s (6 fps) then he could safely leave from the mass center for tumble rates of 5 rpm or lower. The additional velocity should be applied in the spin plane and in a direction to add to the tangential velocity at the moment of exit.

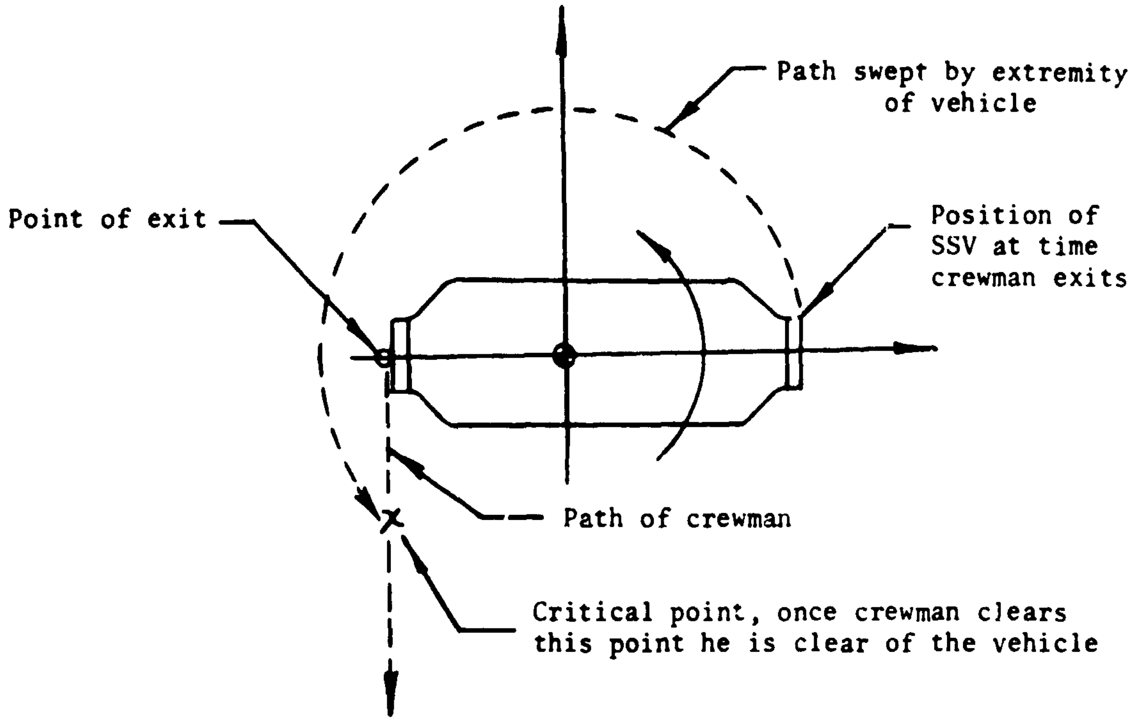


Figure 5-9. Crew Escape From a Tumbling Small Space Vehicle (SSV)

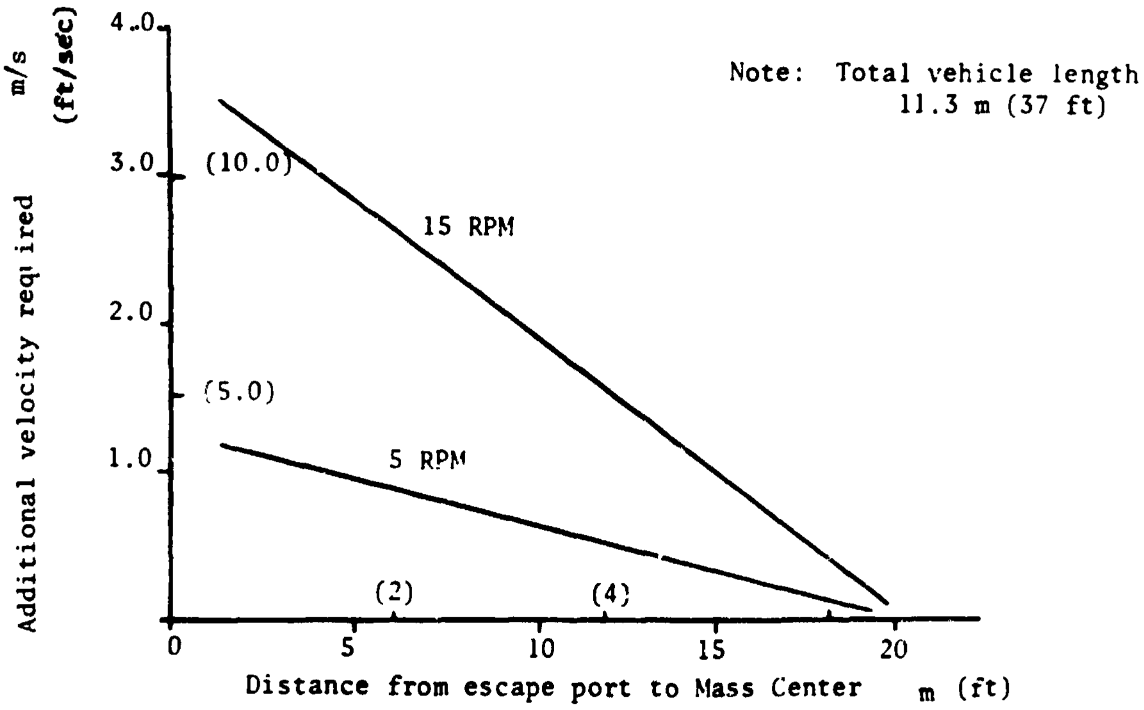


Figure 5-10. Additional Velocity Required to Escape From SSV as a Function of Port Location

In some cases it may be desirable to push off slightly out of the spi.. plane. The advantage is that the crewman need travel only a distance equal to the radius of the vehicle and he will be clear.

5.5.3 Crew Tumbling Arrest Concepts

As has been discussed, the crewman cannot permanently stop his tumbling action without additional equipment to aid him. A number of concepts have been devised to perform this function. These concepts are:

- Manually cranked flywheel despin device - reduces the crewman's body tumbling rate by hand cranking a flywheel

- Reaction control despin device - uses a cold gas reaction control for reducing the tumbling

- Two-man cable despin device - the crew leave the tumbling spacecraft in pairs holding hands and then pay out a cable between them to reduce their angular rate. Rope lengths on the order of 3 m (10 ft) appear to provide tolerable spin rates (approximately 1 rpm). When despun to a comfortable level, the crew could release the cable; however, their linear separation rate could pose recovery problems. The relative translational velocity of the two men while attached to the cable is low (approximately 0.3 m/s, 1 fps), so that the crew will not "crash" into the rescue vehicle.

- Extendable cable despin device - a long cable with a small mass attached to its end is gradually extended.

- Weighted cable despin - a cable with an attached weight is twirled by the crewman about the appropriate axis to bring his head-trunk angular rate to zero. He then lets go of the device, leaving himself despun.

- Extendable rod despin device - two pairs of rods extend in the Y and Z directions from the PLSS. The rods are 23 m (75 ft) long and each weigh about 1 kg (2 lb).

These devices must be able to absorb the angular momentum associated with the maximum tumbling rate considered (14.7 rpm) and the crewman leaving the tumbling spacecraft in a standing position.

The concepts are illustrated and sizing information is given in Figures 5-11 to 5-18.

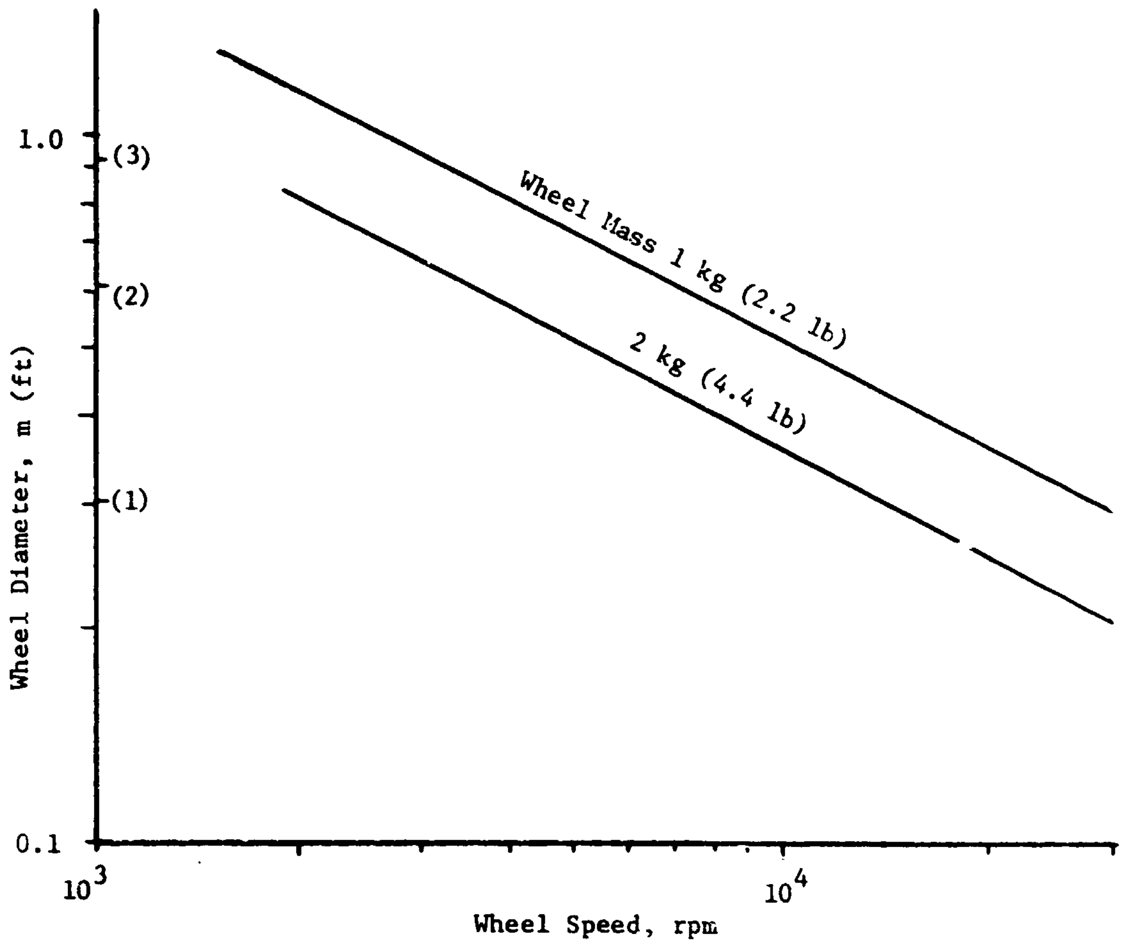


Figure 5-11. Flywheel Characteristics for Manually Cranked Flywheel Despin Device

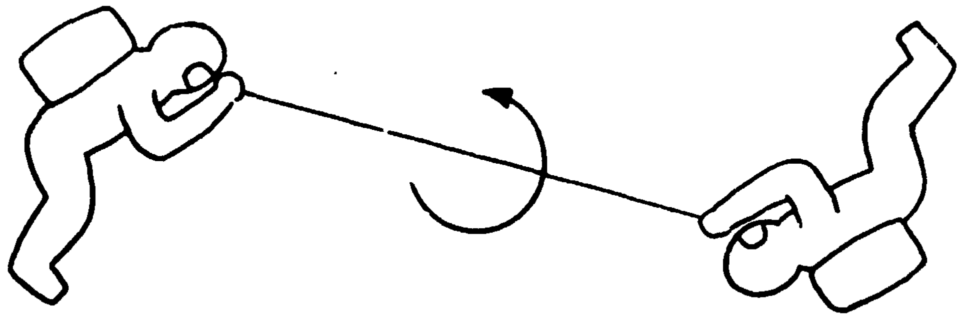


Figure 5-12. Two-Man Cable Despin Device

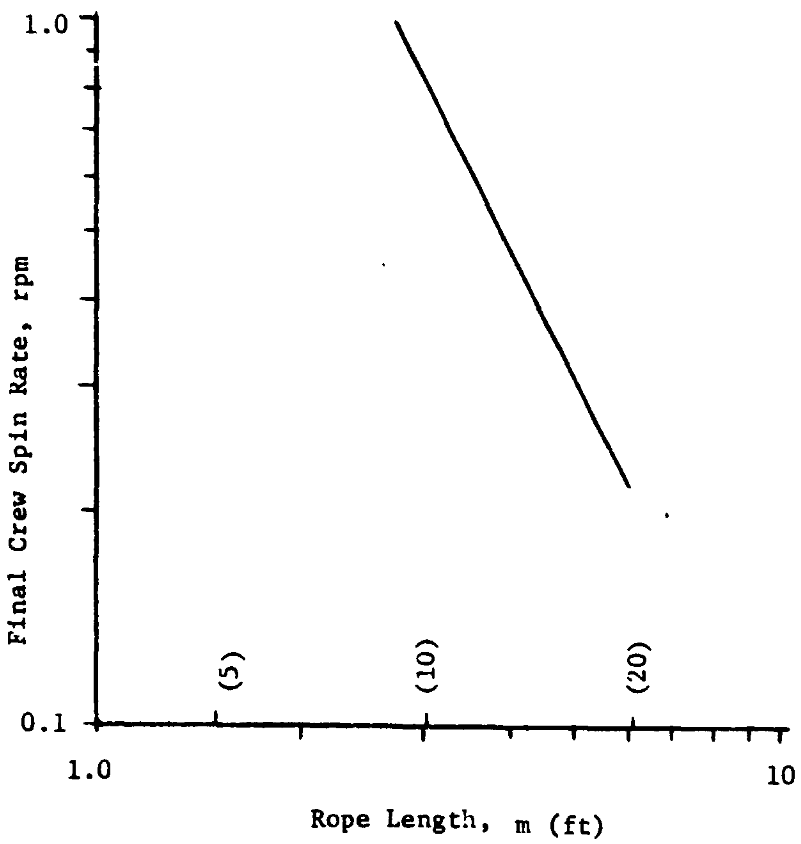


Figure 5-13. Characteristics for Two-Man Cable Despin Device

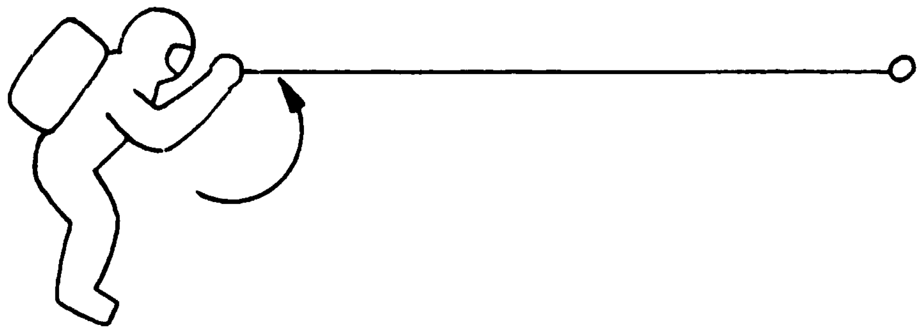


Figure 5-14. Extendable Cable Despin Device

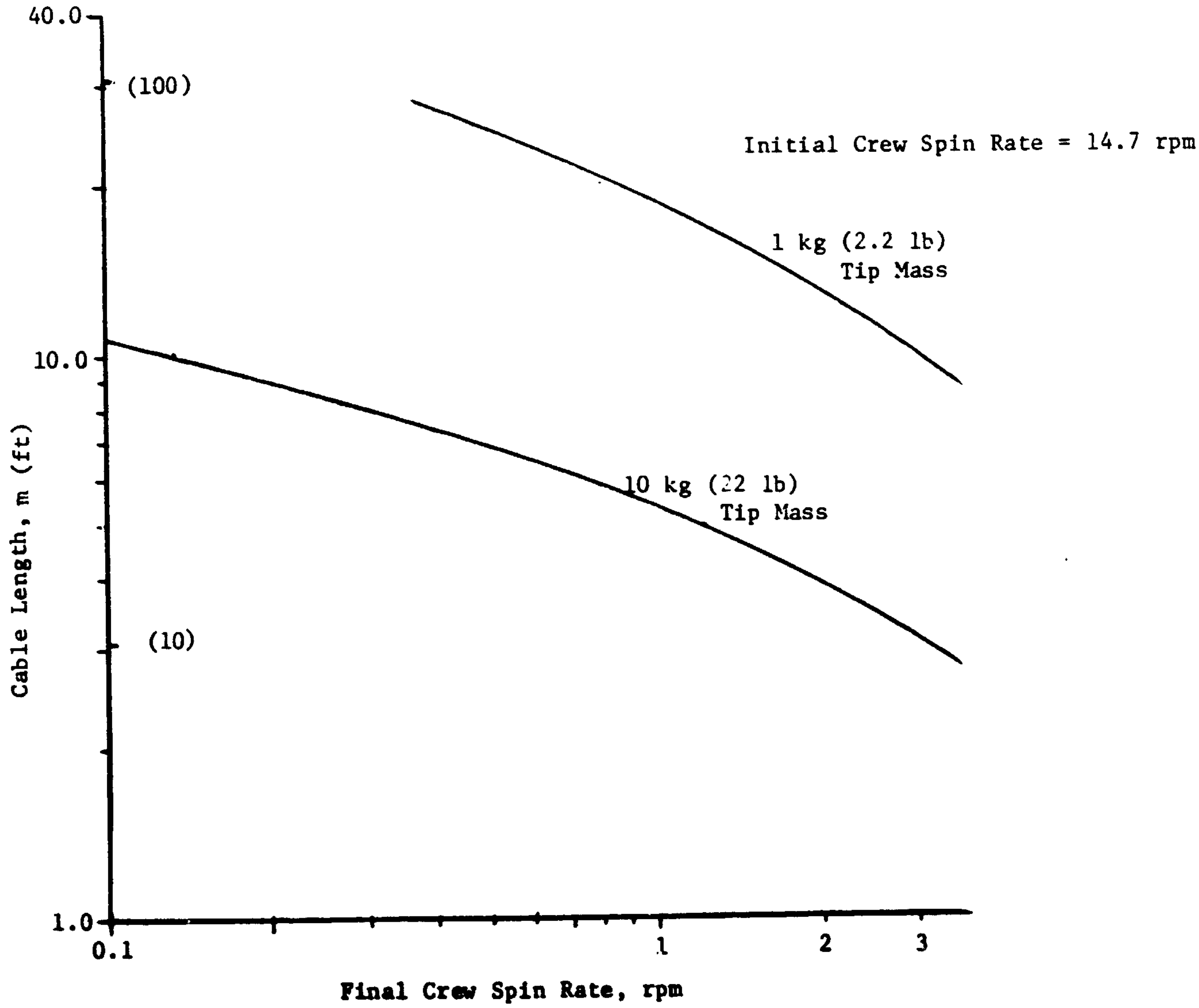


Figure 5-15. Characteristics of Extendable Cable Despin Device

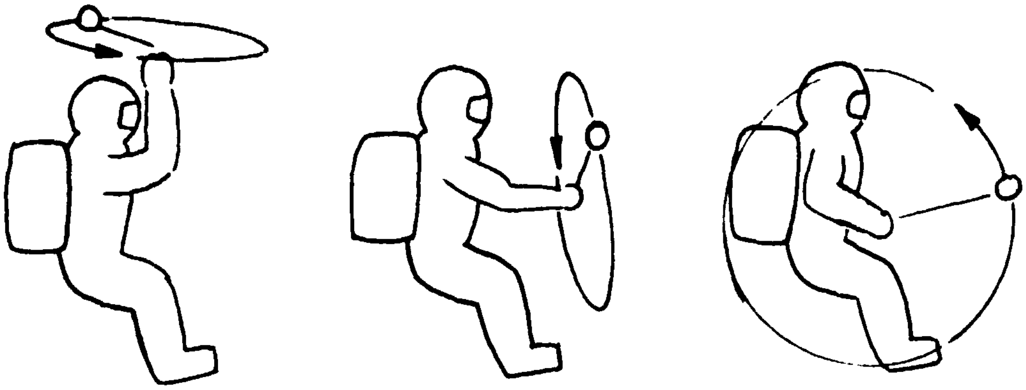


Figure 5-16. Weighted Cable Despin Device

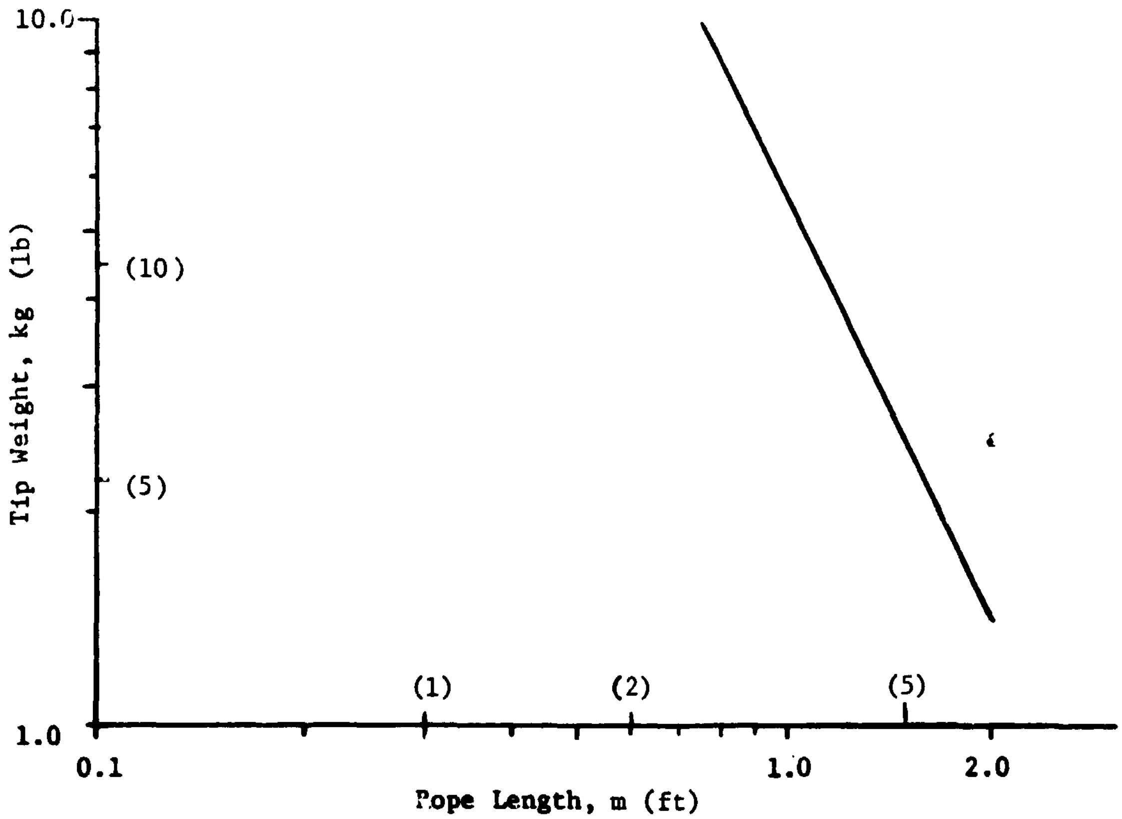


Figure 5-17. Characteristics of Weighted Cable Despin Device

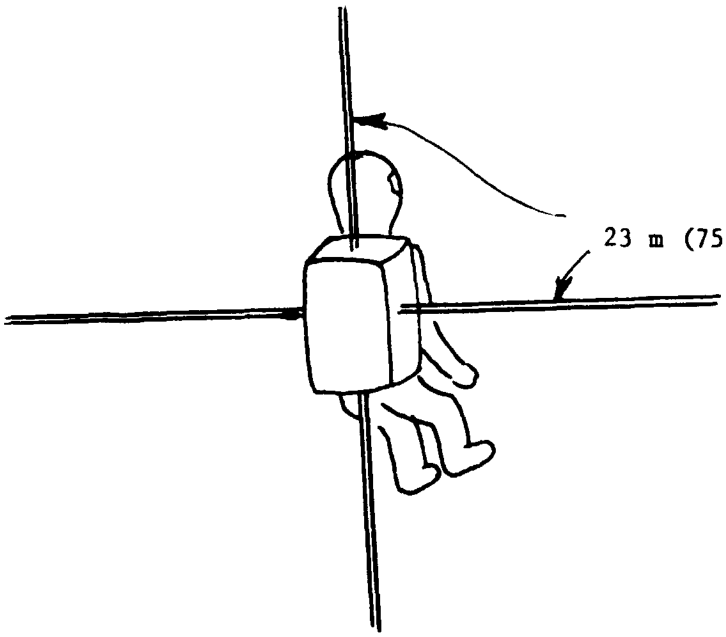


Figure 5-18. Extendable Rod Despin Device

In evaluating the six crew tumbling arrest concepts described, the following evaluation criteria were used:

- The selected concepts should be able to reduce the angular rate from the maximum expected rate (14.7 rpm) to an acceptable rate for recovery by the rescue vehicle (assumed to be 1 rpm or less).
- The devices should be simple to operate, require no specialized training by the crewmen, and pose no additional hazards to them.
- The devices should preferrably make use of materials and equipment readily available, rather than consist of equipment specifically developed for the purpose of arresting tumbling crewmen.
- The devices should not interfere with retrieval of crewmen by the rescuing vehicle.
- The devices should allow usage by incapacitated or unconscious crewmen (with help from fellow crewmen).

Table 5-9 summarizes the evaluation of each of the six concepts considered against the above criteria. The criteria have been phrased so that "Yes" answers are favorable to a concept and "No" answers unfavorable.

The table shows that the two-man despin concept satisfies all the evaluation criteria. None of the other concepts meet all the criteria.

It should be noted that this concept does not necessarily need two crewmen for operation. The second crewman can be replaced by any suitable massive piece of loose equipment secured to the cable. The cable similarly is not a specialized cable, but could be any suitable cable, such as a torn-out length of electrical cable, secured to the crewman's suits in such a way that it can gradually be let out. Strength requirements are minimal, since only small centrifugal forces are experienced.

Table 5-9. Evaluation of Crew Tumbling Arrest Concepts

Concept	Evaluation Criteria					Remarks
	Reduce Rate to 1 rpm	Simple Safe Operation	Use Existing Equipment	Recovery by Rescue Vehicle	Use by Incapacitated Crewman	
• Flywheel Despin	Yes	No	No	Yes	No	—
• Reaction Control Despin	Yes	Yes	No	Yes	No	—
• Two-Man Cable Despin	Yes	Yes	Yes	Yes	Yes	• Buddy system for incapacitated man • Use spare on-board cable
• Extendable Cable Despin	Yes	Yes	Yes	Yes	No	• Use on-board cable and masses
• Weighted Cable Despin	Yes	No	Yes	Yes	No	• Rotating cable is hazard to pressure suit when tumbling • Use spare on-board cable and masses
• Extendable Rod Despin	Yes	Yes	No	Yes	Yes	• Jettison before recovery • Automatic or timed deployment by incapacitated crewmen

6.0 ESCAPE, RESCUE, AND SURVIVABILITY

Crew safety is of prime importance in the design of any manned system, and many provisions are incorporated in spacecraft to prevent accidents and to deal with emergencies. The most desirable type of provisions are those which prevent hazards or accidents from occurring, followed by provisions to deal with emergencies when they have occurred and to restore the spacecraft to a safe operational status. The ultimate safeguard, however, consists of provisions for escape or rescue from a spacecraft which can no longer safely sustain the on-board personnel.

The purpose of this task was to review and analyze escape, rescue and survivability concepts defined in earlier studies, and to determine the feasibility of these concepts for the shuttle, manned sortie modules and modular space station. The most applicable of these concepts were to be identified, and studied for adaptation to crew sizes of up to 6 or 12 men, appropriate to later sortie missions in the orbiter and to the space station. Where adaptation of these concepts is not considered practical, new concepts were to be conceived and their design and operational requirements determined.

Escape, rescue, and survivability are defined as follows:

- Escape: The use of a vehicle, without outside assistance, to effect egress from a manned spacecraft which requires evacuation, and to return to earth.
- Rescue: The use of outside assistance by means of separately based vehicles to effect a return of personnel from the distressed or survival vehicle to a permanent safe haven.
- Survivability: The use of a vehicle or equipment to separate from the distressed spacecraft and provide a safe haven in orbit for personnel until rescue can be effected. This is to be distinguished from on-board survivability, as discussed in Section 4, which refers to ability for personnel to survive until restoration of a habitable environment or until rescue in a separate section of the distressed spacecraft.

Ground rules and assumptions were as follows:

- There is a need for abandonment from each of the three models (shuttle orbiter, sortie module, space station) being evaluated. The reasons for requiring abandonment are not to be analyzed in this task.

- The shuttle will be in inventory for space station operations.
- The sortie module is always attached to the shuttle orbiter while manned.
- The escape, rescue or survivability devices are intact and accessible following the emergency.
- Crew assignment for each model shall be as follows:
    - Shuttle - Minimum of 2 crewmen. The maximum number is that which is compatible with the selected concept(s).
    - Shuttle/Sortie Module - 4 to 10 men, including 2 shuttle crewmen.
    - Space Station - 6 crewmen for initial station and 12 for growth station.
- Adequate time will be available to activate, checkout and deploy any on-board concept considered.
- Escape and survivability concepts allow personnel abandonment of the distressed vehicle within hours of the emergency. Rescue concepts can reach the distressed vehicle or the survivability vehicle within a few days.

No attempt has been made in this study to determine possible causes for requiring abandonment of the spacecraft, to determine the statistical probability, absolute or relative, of such causes, or to determine how much time is available to the on-board personnel for escape or rescue. In all the evaluations it is assumed that the potential escape, rescue, or survivability devices are accessible to the personnel, that they are able to operate them, and that they have sufficient time to do so.

6.1 CONCLUSIONS AND RECOMMENDATIONS

Conclusions and recommendations reached are as follows;

- The shuttle orbiter should be the primary vehicle for dealing with emergencies of manned vehicles in earth orbit. A shuttle orbiter should be available for rapid emergency rescue whenever manned earth orbital flight is in progress. This need not be a dedicated rescue shuttle or orbiter, but normal operational vehicle on which any of a variety of rescue kits could replace the planned payload in an emergency.

- If there is a time period at the beginning of the shuttle program (or during the mature shuttle operational period) when shuttle rescue is not possible because of the non-availability of a second shuttle for rescue, launch pad, or other reason, an Apollo command module, called an Escape CM, should be carried in the orbiter cargo bay as an escape vehicle. This can be a refurbished command module with up to six seats (as required) and with capability for reentry from earth orbit and water landing. The CM should be pressurized at 8 psi, to allow rapid shirtsleeve entry of the personnel without the danger of getting "bends". This Escape CM is the most cost effective of the escape and rescue vehicles considered.

- If a quicker escape or rescue capability is required from the shuttle orbiter, sortie modules or space station that can be provided for by the emergency shuttle rescue, one of the following approaches should be used:

  - The first approach is to include a stripped-down Apollo command module as a survivability escape, called a Survivability CM, (i.e., a "Lifeboat") in the orbiter cargo bay. This will require no heat shield structure or parachute system, and possibly only a minimum restraint system instead of seats.

  - The second approach is to equip a manned sortie module on the orbiter or two or more modules on the station as survivability modules. These require separation capability, an emergency life support system, an attitude stabilization system for coarse attitude hold and for docking, and an earth communication capability. Survivability will be needed for a number of days in orbit, until a shuttle rescue vehicle can pick the survivability capsule up and return it to earth.

  - Another possible approach is to develop a simple, low cost survivability capsule, called an MSV (Modular Survivability Module), particularly for use in the orbiter cargo bay. It should accommodate the maximum number of on-board personnel.

- Refurbished Apollo command modules (Escape CM's) can be used as escape vehicles. One would be required on shuttle missions; the space station would require more than one to provide access from multiple points. This approach is only feasible for complements of up to 6 personnel.

o At some appropriate time in the shuttle program a study should be initiated to determine whether escape or survivability capability will be required. The study should consider potential time criticalities of emergencies; availability and time of shuttle rescue; and design and cost studies of the recommended escape and survivability concepts.

6.2 CONCEPTS CONSIDERED

6.2.1 Escape Concepts

The following eleven escape concepts have been considered:

- o Airmat (Goodyear)
- o Rib Stiffened (NR)
- o Paracone (MDAC)
- o Moose (GE)
- o Encap
- o Egress (Martin-Marietta)
- o Life Raft (GE)
- o Lifting Body (Northrop)
- o EEOD (NASA/Lockheed)
- o Spherical Heat Shield (NR)
- o Apollo Command Module (Escape CM) (NR)

These concepts, which were selected from previous studies, are illustrated in Figure 6-1, and some of their characteristics are described. Although the concepts selected for evaluation do not include all concepts defined in the surveyed studies, they are representative of the scope of the functional, operational, dimensional, and weight characteristics of all concepts reviewed.

The CM was included because a number of used CM's are expected to be available in the time period considered, and these could be refurbished and modified as necessary for use as escape vehicles. The service module is not needed, and probably will not be available. A retro-rocket package, as shown in the sketch of the Escape CM, may however be needed for deorbit.

6.2.2 Rescue Concepts

Two rescue concepts have been considered. These are:

- o The shuttle booster and orbiter

- o The Apollo Command and Service Module (called Rescue CSM) on an S-IB or Titan booster

The rescue shuttle is a normal shuttle booster and orbiter, whose mission is changed to a rescue mission as soon as the emergency has occurred. For rescue of personnel in excess of the normal shuttle passenger compartment capacity, a rescue kit can be added at short notice in the cargo bay.

The Rescue CSM is similar in concept to the use of the CSM as a rescue vehicle on the Skylab program. In this program a "rescue kit" is kept available at the launch site in case of need. This consists mainly of a kit to convert the 3-man CM into a 5-man vehible by the addition of 2 extra seats.

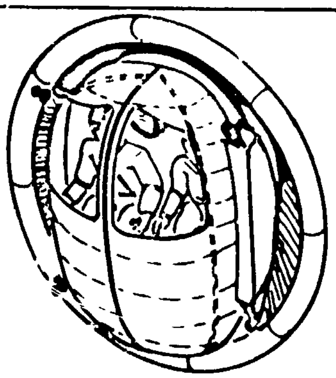
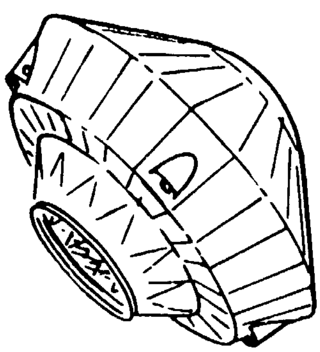
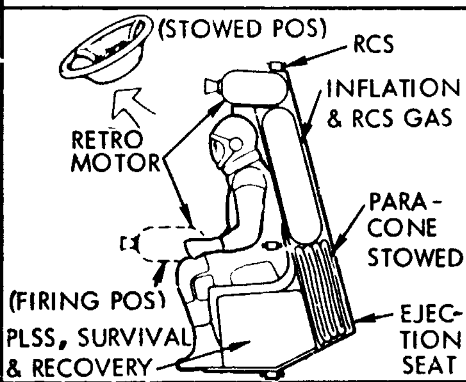
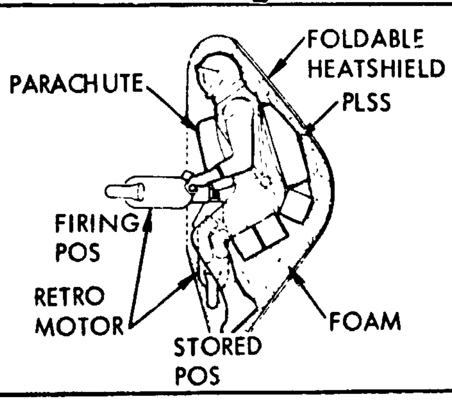
<table>
<tr><th>TYPE</th><th>CONCEPT NAME</th><th>SCHEMATIC PRESENTATION</th><th>CHARACTERISTICS</th></tr>
<tr><td rowspan="4">DEPLOYABLE</td><td>AIRMAT
(GOODYEAR)</td><td></td><td>• 2 MAN
• SUITS REQUIRED
• INFLATABLE
• EJECTION SEAT
• 518 KG (1140 LB)
• NEW TECHNOLOGY REQUIREMENTS
  • FLEXIBLE HEATSHIELD
  • MATERIAL</td></tr>
<tr><td>RIB STIFFENED
EXPANDABLE
(NR)</td><td></td><td>• 3 MAN
• SHIRTSLEEVE ENVIRONMENT
• MECH RIGID
• CANISTER STORED
• 660 KG (1452 LB)
• NEW TECHNOLOGY REQUIREMENTS
  • ARTICULATING RIB-TRUSS STRUCTURE
  • MATERIAL</td></tr>
<tr><td>PARACONE
(MDAC)</td><td>
</td><td>• 1 MAN
• SUIT
• INFLATABLE
• 192 KG (425 LB)
• NEW TECHNOLOGY REQUIREMENTS
  • LARGE INFLATABLE AND DEPLOYABLE STRUCTURE
  • MATERIAL</td></tr>
<tr><td>MOOSE
(GE)</td><td>
</td><td>• 1 MAN
• SUIT
• HAND-HELD RETRO
• ALL EQUIPMENT CARRIED EVA
• FOAM-IN-PLACE
• 215 KG (475 LB)
• NEW TECHNOLOGY REQUIREMENTS
  • FOAM IN SPACE
  • FOLDABLE HEAT SHIELD</td></tr>
</table>

Figure 6-1. Candidate Escape Concepts

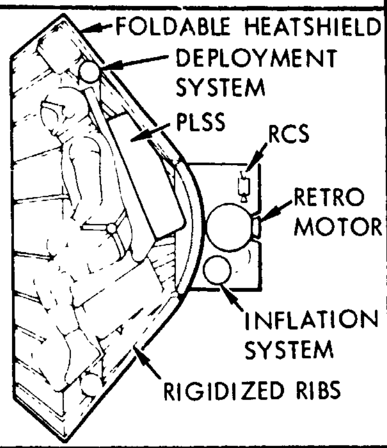
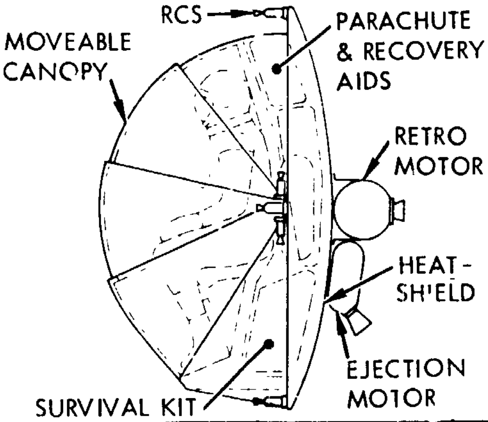
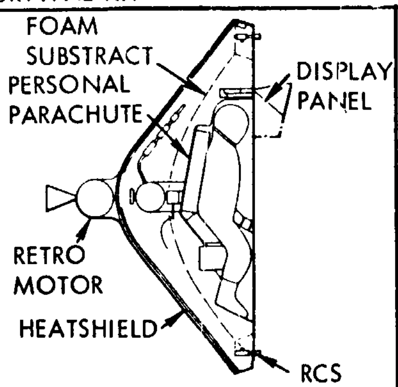
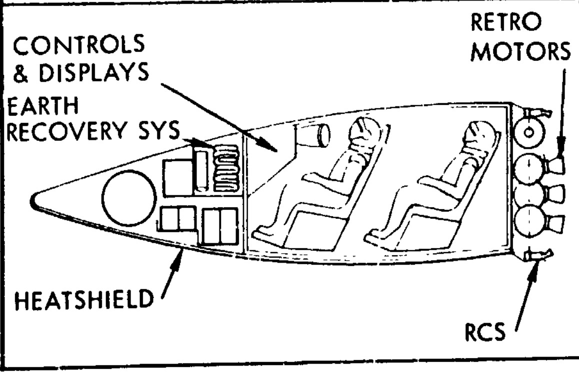
TYPE	CONCEPT NAME	SCHEMATIC REPRESENTATION	CHARACTERISTICS
DEPLOYABLE (CONT'D)	ENCAP		• 1 MAN • SUIT • EVA • MECH RIGID • 24 KG (588 LB) • NEW TECHNOLOGY REQUIREMENTS • MECHANICAL DEPLOYMENT MECHANISM • FOLDABLE HEAT SHIELD
RIGID	EGRESS (MARTIN-MARIETTA)		• 1 MAN • SHIRTSLEEVE ENVIRONMENT • EJECTION SEAT • 370 KG (820 LB) • NEW TECHNOLOGY REQUIREMENTS • MOVABLE CANOPY NEW HEAT SHIELD • MODIFIED B-58 CAPSULE
	LIFERAFT (GE)		• 3 MAN • SUITS REQUIRED • PERSONAL CHUTES REQUIRED • 420 KG (936 LB) • NEW TECHNOLOGY REQUIREMENTS • NEW HEAT SHIELD • FOAM MATERIAL
	LIFTING BODY (NORTHRUP)		• 3 MAN • SHIRTSLEEVE ENVIRONMENT • 1950 KG (4330 LB) • NEW TECHNOLOGY REQUIREMENTS • NEW HEATSHIELD • REENTRY TECHNIQUE • HIGH SPEED PILOT TECHNIQUES

Figure 6-1. Candidate Escape Concepts (Cont)

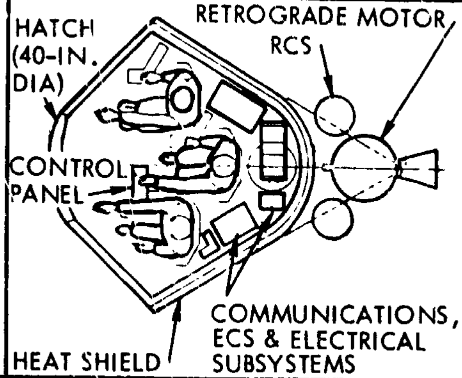
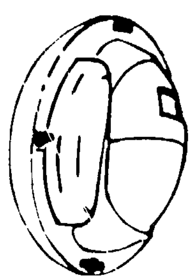
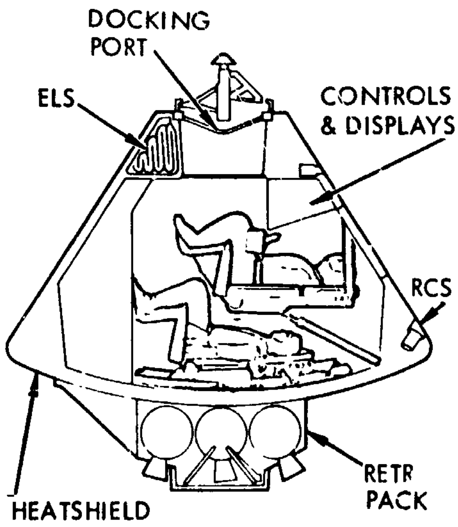
TYPE	CONCEPT NAME	SCHEMATIC REPRESENTATION	CHARACTERISTICS
RIGID (CONT'D)	*EEOED (NASA/ LOCKHEED) *EMERGENCY EARTH ORBITAL ESCAPE DEVICE		• 3 MAN • SHIRTSLEEVE ENVIRONMENT • 1240 KG (2769 LB) • NEW TECHNOLOGY REQUIREMENTS • NEW HEATSHIELD
	SPHERICAL HEAT SHIELD (NR)		• 2 MAN • SHIRTSLEEVE ENVIRONMENT • 445 KG (985 LB) • NEW TECHNOLOGY REQUIREMENTS • NEW HEATSHIELD
	APOLLO ESCAPE CM (NR)		• 2-6 MAN • SHIRTSLEEVE • ≈ 4500 KG (10,000 LB) • NEW TECHNOLOGY REQUIREMENTS • NONE

Figure 6-1. Candidate Escape Concepts (Cont)

For use as a rescue vehicle for the shuttle and space station operations, the CM can be modified to accept up to a total of 6 men. With a launch crew of 2, this can be used to rescue up to 4 men.

This Rescue CSM concept is practical only while a boost vehicle is available. The service module is needed to provide power and propulsion from launch through deorbit. If an S-IB booster is not available, the Rescue CSM could be launched on a Titan.

Rescue of a distressed vehicle by a space station already in orbit does not appear practical because of the space station limited capability to change its orbit. This was therefore not considered as a practical candidate.

6.2.3 Survivability Concepts

Five survivability concepts have been considered. These are:

- Cocoon
- Sortie module
- Space station module
- Apollo command module (Survivability CM)
- Modular survivability vehicle (MSV)

The Cocoon is a concept by the General Electric Company. It consists of encapsulating individual suited crewmen in foamed plastic, to afford thermal and other protection until rescue. This device is relatively light and simple.

The sortie module and the space station module as survivability concepts would be designed and operated so that in an emergency they can be separated from the parent vehicle (the orbiter and the space station respectively) and provide the necessary functions for life support and for being rescued.

Refurbished Apollo command modules can be adapted as survivability vehicles (Survivability CM's). The stripped down Survivability CM could accommodate considerably more personnel than the normal complement. Figure 6-2 shows how 8 men could be accommodated under emergency conditions and still allow sufficient room for some mobility and for personal hygiene purposes. The figure shows that it is possible to accommodate 10 men, and as an extreme upper limit, 12 men. If weight is a limitation, the whole of the outside heat shield structure could be removed, and an insulation blanket substituted for thermal and meteoroid protection. External systems, such as the parachute and uprighting systems, could also be removed.

The modular survivability vehicle is a survivability concept specifically adapted for use on orbiter, sortie missions and on the space station. A design concept for this is shown in Figure 6-3 and is capable of accommodating up to 12 men for approximately 2 or 3 days under emergency conditions. It is about the same size as an Apollo CM. The analysis showed that if a 12-man capacity is required at some time, it does not make sense to consider a smaller capsule in addition to a smaller capsule for smaller complements. The MSV is described in Section 6.6.

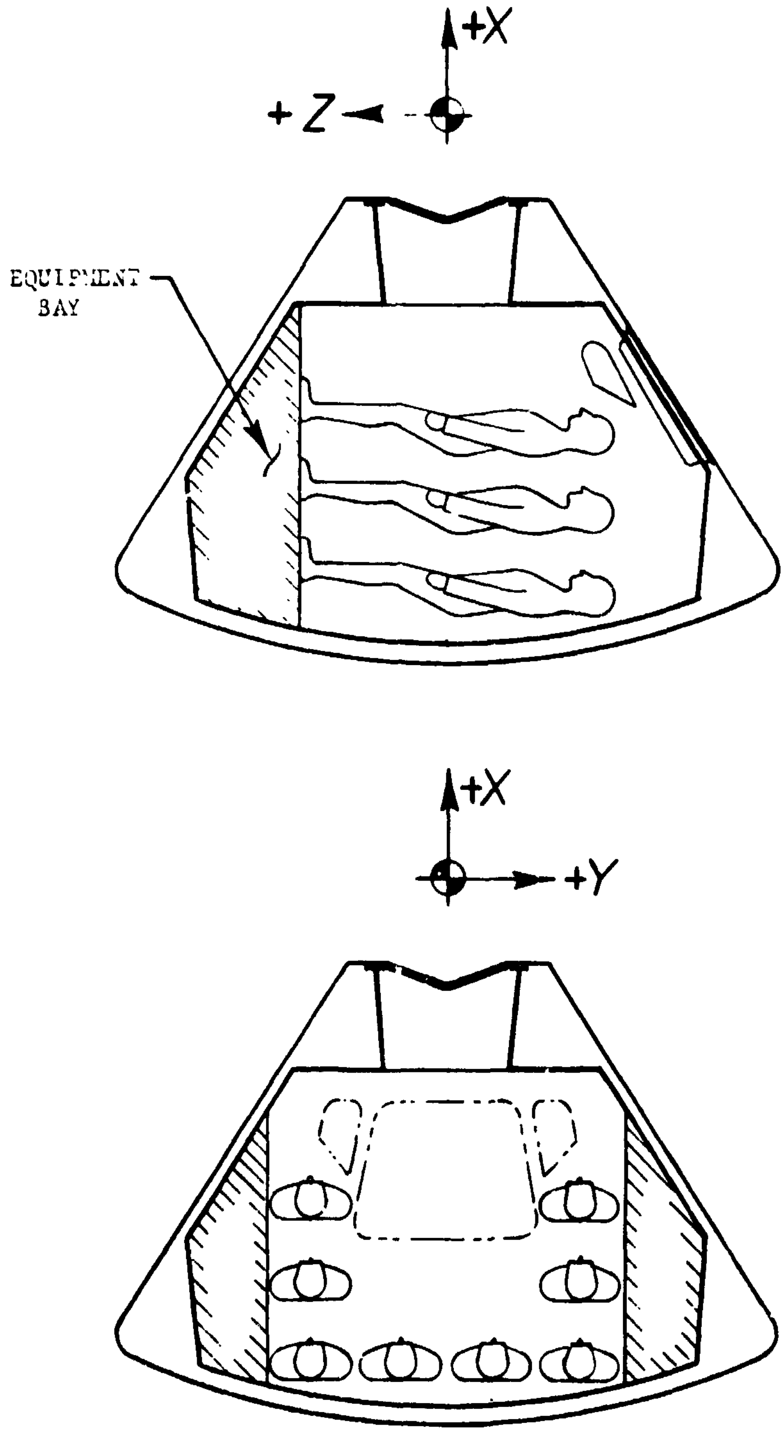


Figure 6-2. Apollo Command Module Modified as 8-Man Survivability CM

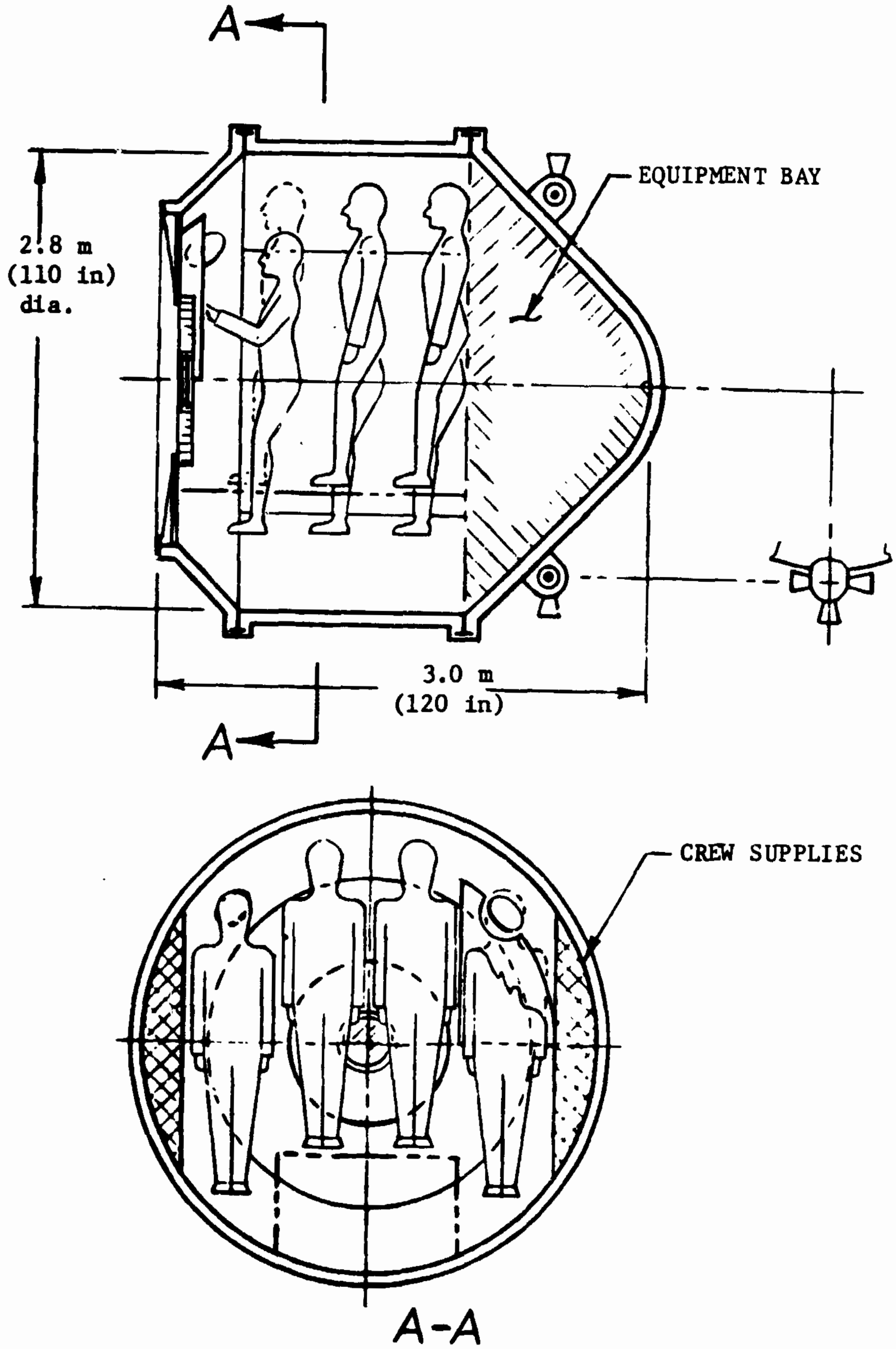


Figure 6-3. **Two- to Twelve-Man Modular Survivability Vehicle Concept**

6.3 EVALUATION

The preferred concepts in each of the three categories of escape, rescue and survivability, were determined on the basis of the following evaluation criteria.

- Shirtsleeve - Shirtsleeve operations are preferred to suited operations since shirtsleeve operations improve personnel reaction time and provide better capability to deal with injured or incapacitated personnel.

- Buddy System - Concepts which use the buddy system (i.e, can accommodate 2 or more men) are preferred over single man concepts since they allow for attending to injured or incapacitated personnel.

- Cost - The recommended approach must have a low total cost, i.e., development, recurring and operational. Recurring costs include costs of manufacturing, testing, and checkout. Operational costs include cost of the supporting launch vehicles and launch facilities, and of any required recovery operations.

- Technology - Approaches using state-of-the-art are preferred to ones requiring new technology development.

- Development Risk - Proven concepts are preferred to new ones since they reduce program risk. New concepts with minimum development risk are preferred to concepts with high development risk.

- Launch Vehicles - Concepts which can be used without a separate launch are preferred over those which require a separate launch or those which require a dedicated spacecraft and launch vehicle.

- Recovery - Return of the personnel in an orbiter at the shuttle landing site is preferred to a water landing because it does not require complex recovery operations.

- Payload Impact - Concepts which have the least impact in restricting the orbiter or sortie payloads because of weight or volume are preferred.

The comparative evaluation of the various escape rescue and survivability concepts against the evaluation criteria is shown in Table 6-1. Selection of the preferred concepts in each of the three categories can be made independently.

6.3.1 Preferred Escape Concept

The refurbished Apollo **Escape CM with a retro-rocket package is the** preferred escape concept.

Comparison of the various factors in Table 6-1 indicates that the decision lies broadly between the new concepts on the one hand, and the Apollo **Escape CM** on the other. The most attractive of the new concepts appears to be the Spherical Heat

Table 6-1. Evaluation Escape, Rescue, and Survivability Concepts for 6 Men

Concept	Crew Size	Shirt-Sleeve	Cost ($M)	Technology	Development Risk	Launch Vehicles	Recovery	Payload** Impact
Escape								
Airmat	2	No	93	New	High	No	Water	Low
Rib stiffened	3	Yes	103	New	High	No	Water	Low
Paracone	1	No	84	New	High	No	Water	Low
Moose	1	No	100	New	High	No	Water	Low
Encap	1	No	100	New	High	No	Water	Low
Egress	1	Yes	79	New	Medium	No	Water	Medium
Life raft	3	No	86	New	High	No	Water	Low
Lifting body	3	Yes	196	New	Medium	No	Water	Medium
EEOD	3	Yes	108	New	Medium	No	Water	Medium
Spherical heat shield	2	Yes	87	New	Medium	No	Water	Low
Apollo Escape CM	2-6	Yes	35	Current	Very low	No	Water	High
Rescue								
Shuttle	12	Yes	0-1 launch	None extra	Low	***only if needed	Shuttle	None
Apollo Rescue CSM	2-4	Yes	Very high	Current	Low(S-IB) Med(Titan)	Yes	Water	None
Survivability*								
Cocoon	1	No	Med-High	New	High	***Only if needed	Shuttle	Low
Sortie module	12	Yes	Med-High	Current	Medium		Shuttle	Low
Space Station Module	12	Yes	Med-High	Current	Medium		Shuttle	N/A
Apollo Survivability CM	8	Yes	Med-High	Current	Medium		Shuttle	High
Modular Survivability Vehicle (MSV)	12	Yes	Med-High	Current	Medium		Shuttle	Low

*Assumes shuttle used for rescue
**Low = 2000 kg (4500 lb), high = 4000 kg (9000 lb)
***Launch vehicles are used only if a rescue or survivability situation arises. Dedicated launch vehicles not required.

Shield, since this has all the desirable features at nearly the lowest cost of the new concepts. The comparison of this with the Escape CM is summarized as follows:

	Spherical Heat Shield	Escape CM
Cost	High	Moderate
Technology	New	Current
Development Risk	Medium	Very low
Payload Impact	Low	High

The deciding factor appears to be the importance of the impact of the weight in reducing the payload capacity. If the weight of 5,900 kg (13,000 lb) can be tolerated, the Escape CM is obviously the preferred escape concept. If on the other hand potential reduction in escape system weight from 5800 to 1340 kg (13,000 to 3,000 lb) is vital, the Spherical Heat Shield concept is preferable.

6.3.2 Preferred Rescue Concept

The Shuttle is the preferred rescue concept. The comparison of the Shuttle rescue and the Apollo CSM rescue concepts in Table 6-1 shows that the advantages are all in favor of using the Shuttle if it is available. If a shuttle is not available for use as a rescue vehicle, escape or survivability concepts appear preferable to maintaining a Rescue CSM capability.

6.3.3 Preferred Survivability Concepts

The recommendation is to consider four concepts as options for survivability concepts, i.e.,::

- o Sortie Module
- o Space Station Module
- o Apollo Survivability
- o Modular Survivability Vehicle (MSV)

Comparison of these in Table 6-1 shows that all four concepts are practical. The decision as to which, if any, is the preferred concept can be left to later studies, when more detailed design and cost data are available.

Use of the sortie module and space station modules as survivability vehicles would be cost effective if these modules are in any case required to have a large degree of self sufficiency, e.g., in the environmental control and life support. On the other hand there may be many different sortie modules in the program, and it may impose a large cost penalty to incorporate survivability provisions on each module. In such a case it may be preferable to use a single MSV design for all sortie missions. The MSV could also be used on orbiter missions which do not include a habitable sortie module. The Survivability CM could be attractive if a survivability vehicle appears necessary for a limited number of missions at relatively short notice. Development of the Survivability CM from existing CM's could require considerably less lead time than development of a new vehicle such as MSV.

6.4 INTEGRATED ESCAPE, RESCUE AND SURVIVABILITY APPROACH

Having determined the preferred concepts in each of the three categories of escape, rescue and survivability, an integrated approach must be synthesized. This integrated approach must satisfy the two following criteria:

- Commonality - The recommended concept or combination of concepts must be capable of providing for the survival of all on-board personnel on the orbiter, sortie module, or space station following an emergency. That is, a recommendation which cannot deal with all the on-board personnel and all the vehicles is not acceptable.

- Time Criticality - If it is considered desirable to be able to abandon the distressed spacecraft within hours rather than days, the preferred approach must include escape or survivability concepts since rescue may take as long as a few days. Since it is only possible to determine whether the time criticality of emergencies may be hours or days (or minutes for that matter) on a statistical basis, this is treated as a program decision to be made at a later date, and recommendations are made for either option.

The candidate concepts are:

- Escape: Apollo Escape CM

- Rescue: Shuttle

- Survivability: Sortie module, Space Station Module, Apollo Survivability CM or Modular Survivability Vehicle (MSV)

In addition, certain assumptions can be made relating to the expected development of the Shuttle, Sortie and Space Station programs. These can be summarized as follows:

- In the early phases of the Shuttle program, the following conditions are expected:

  - A shuttle rescue capability may not be available because of limited orbiters, boosters or launch pads.

  - The maximum number of personnel in the orbiter will probably not exceed 4, possibly 6.

  - The payloads will use less than the full weight or volume capacity of the orbiter.

  - The risk of an emergency occurring is greater in this time period.

- When the Shuttle program matures, personnel complements may increase, as a maximum, to about 10 or 12 men. Payloads will generally use maximum payload weight capacity, but not maximum volume. Some shuttle payloads, such as tugs or large telescopes, may however occupy the full cargo bay.

- By the time a Space Station becomes operational, the Shuttle program will be operating on a routine basis with sufficient vehicles and facilities for emergency rescue operations.
- Only a limited number of Apollo command modules will be available for refurbishment. Service modules, S-IB's and possible Titans will be even more limited in availability, and will not be replaceable if used. These propulsion vehicles will only be available in the early phases of the Shuttle program because of potential aging problems.

The logic used for determining the integrated approach is shown in Figure 6-4. Different options are available, and different approaches recommended, according to the answers to the two key questions (shown in the diamonds in the figure):

- Is Shuttle rescue available?
- If so, is it quick enough to reach the distressed spacecraft on time?

As pointed out earlier, these questions cannot be answered in this study, and will remain as program decisions to be made at a later date. The conclusions are therefore presented as depending on the answers to these questions.

A. <u>Shuttle rescue is available and is quick enough to reach distressed vehicle in time</u>

Shuttle rescue is recommended as the primary vehicle for deal with emergencies of all manned vehicles in earth orbit because of the cost effectiveness of the Shuttle as a rescue vehicle (if rescue is not needed, costs are practically zero).

B. <u>Shuttle rescue is available but may not be quick enough to reach distressed vehicle in time.</u>

The specific concepts recommended for orbiter, sortie and space station vary, as follows:

- <u>Orbiter</u>. Use the Escape CM as an escape vehicle; or the Survivability CM or a specifically designed new MSV as a survivability module.
- <u>Sortie</u>. Use the Escape CM as an escape vehicle; or incorporate survivability requirements in the sortie module.
- <u>Space Station</u>. Use two Escape CM's as escape vehicles (for a 6-man station); or incorporate survivability in two space station modules. Two vehicles are needed for a station, because the station is expected to have two independent volumes, and a need for abandonment would indicate that at least one volume has become damaged or otherwise unavailable.

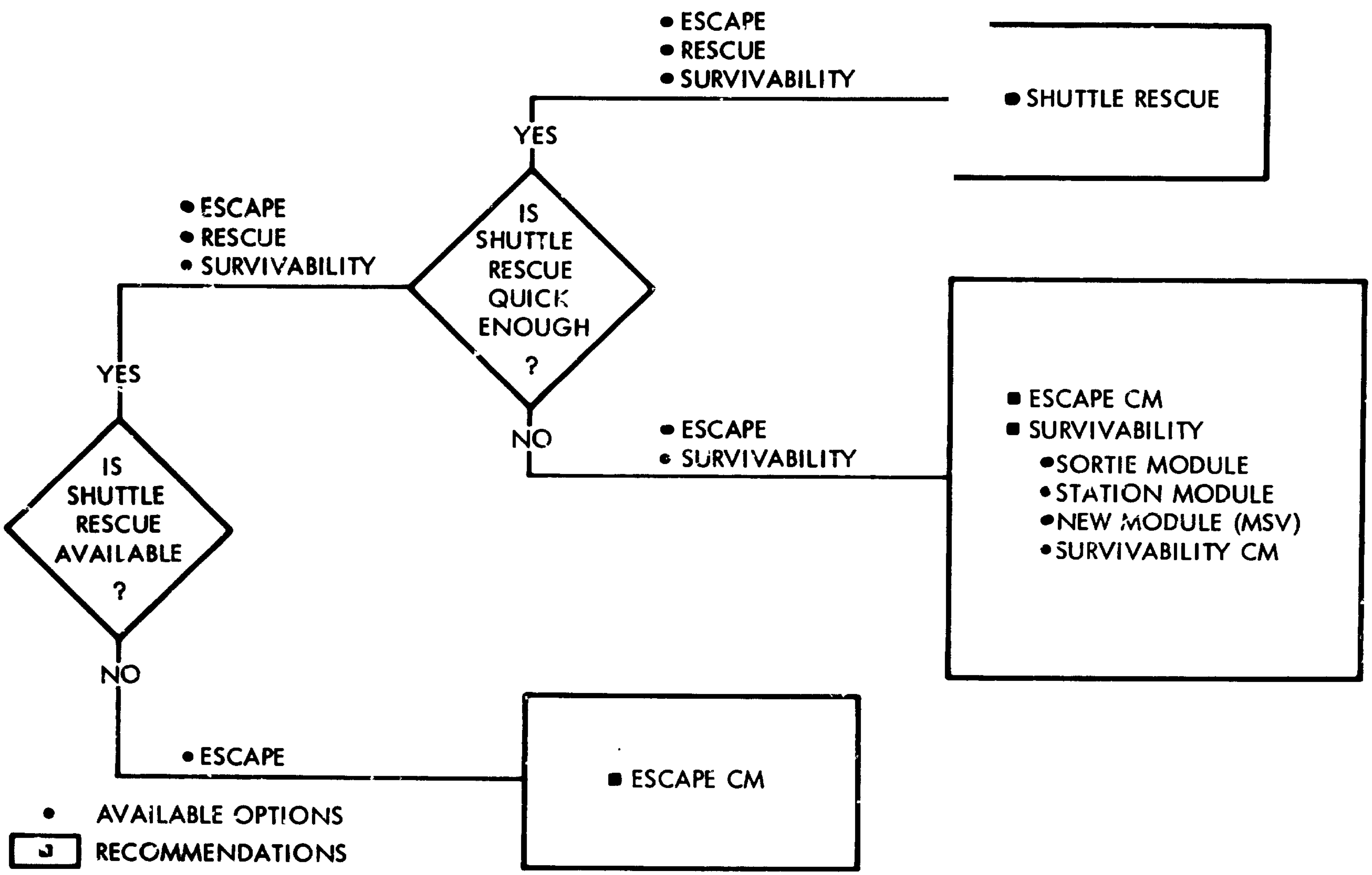


Figure 6-4. Integrated Approach Options and Recommendations

C. Shuttle rescue is not available.

The Escape CM is recommended for the orbiter on sortie and other missions. Since the Escape CM can hold 6 men at a maximum, this means that flights under such conditions should be limited to a maximum of 6 men.

Since it has been assumed that the Space Station will only operate when the Shuttle is fully operational and available for rescue, the question of escape is not applicable.

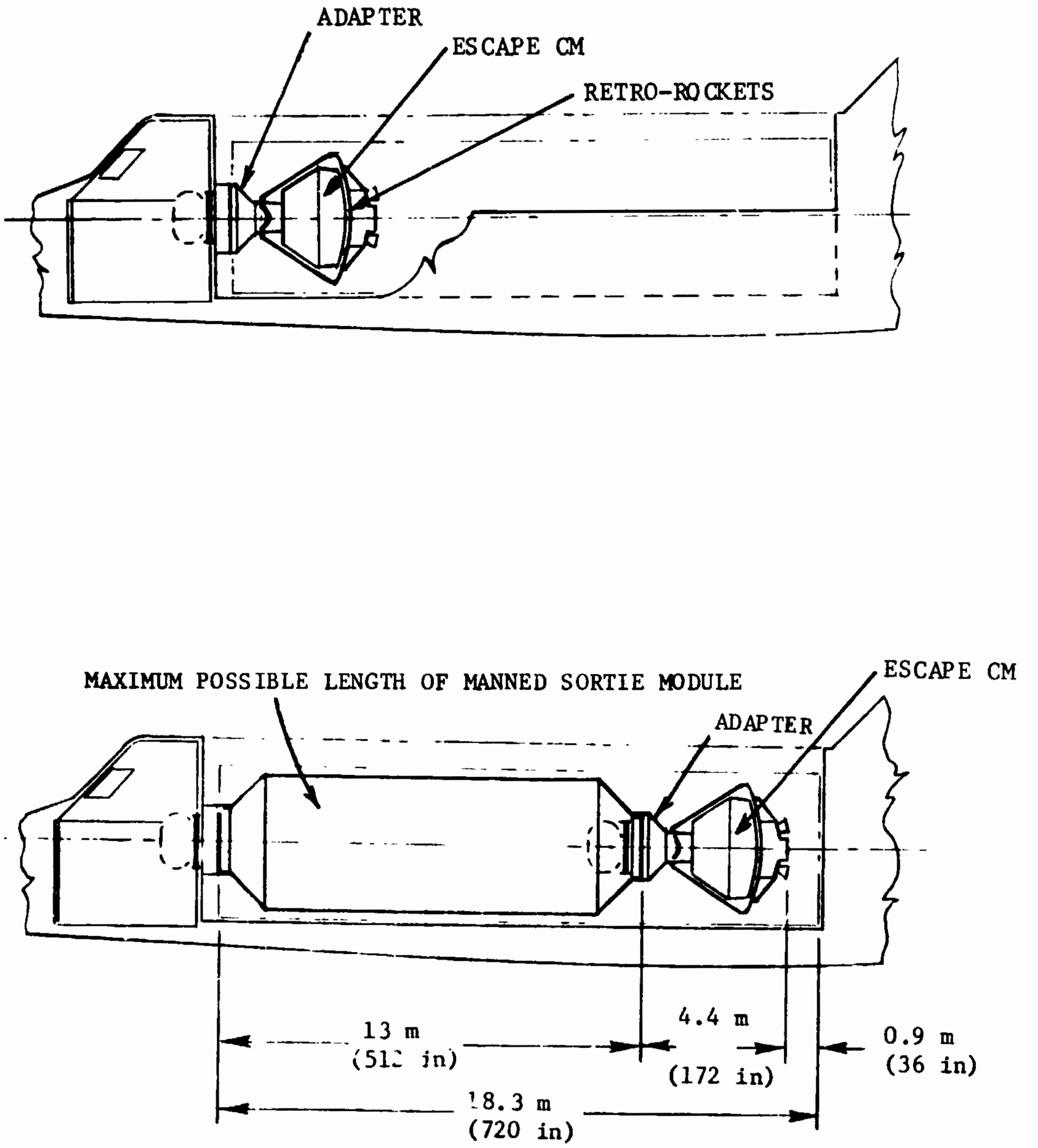


Figure 6-5. Escape Apollo Command Module in Orbiter Cargo Bay

6.5 INTEGRATION OF ESCAPE COMMAND MODULE IN ORBITER AND SPACE STATION

Typical integration of the Apollo command module as an escape concept in an orbiter with and without a sortie payload is shown in Figure 6-5. For shuttle sortie missions with a crew and passenger complement of up to 6 personnel, and with a sortie module or pallet payload, a single modified Apollo Escape CM can be used.

Figure 6-5 illustrated how 6 men can be accommodated in an Escape CM. Because water landing can be ensured, only very little seat stroking is required.

A typical example of two 6-man Escape CM's, one attached to each volume of a 2 volume NR station, is depicted in Figure 6-7. For the 12-man station, the alternative exists for two 6-man devices for each station volume.

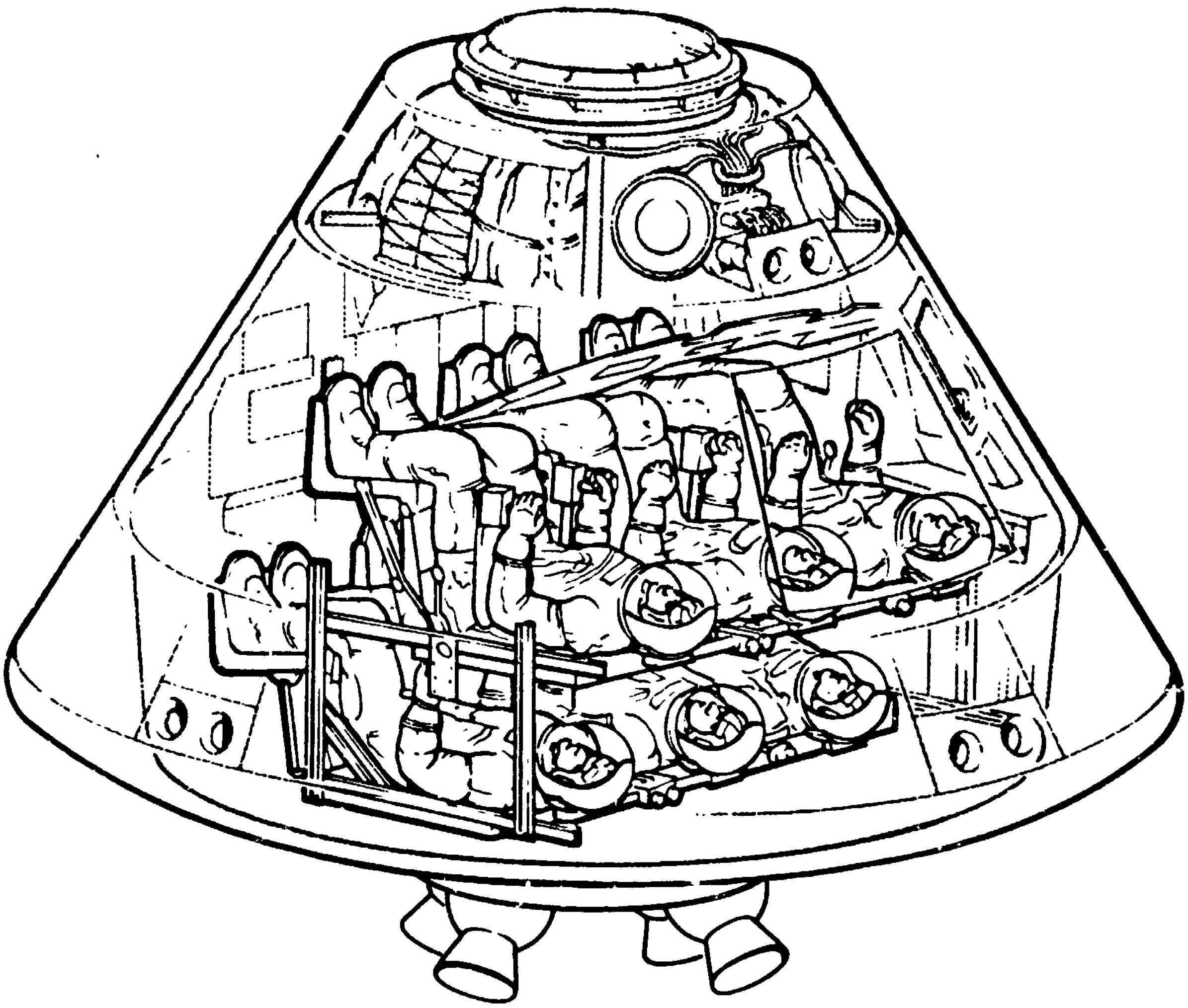


Figure 6-6. Apollo Command Module Modified for Six Men

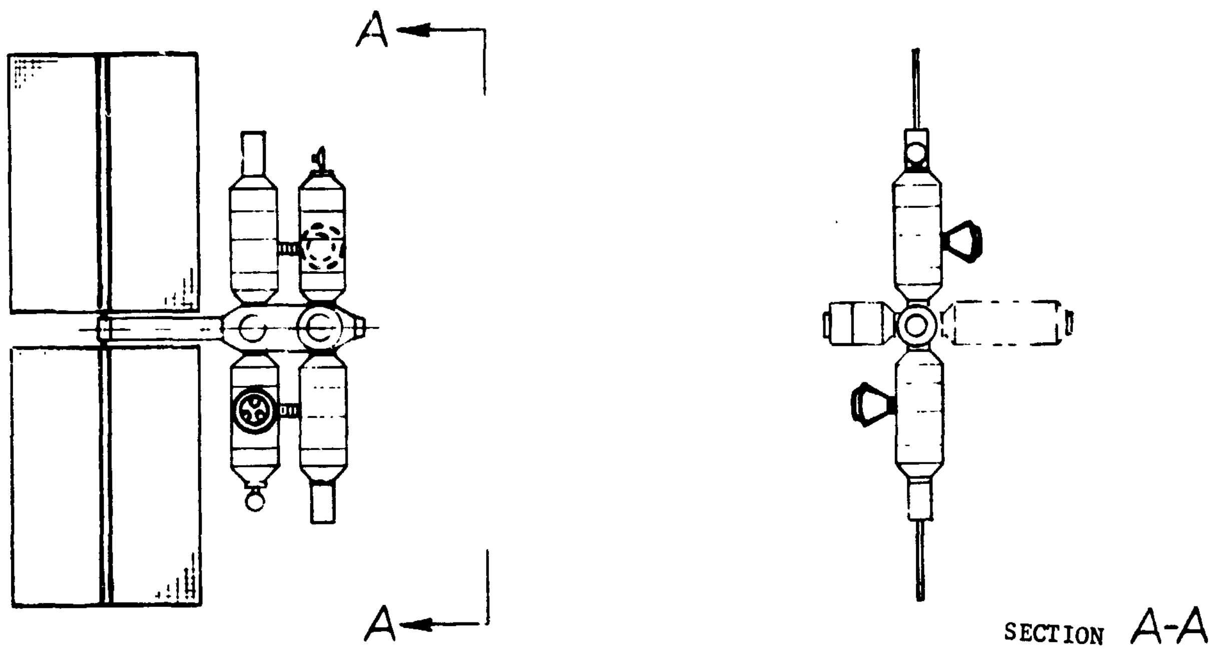


Figure 6-7. Apollo Escape CM's on 6-Man Space Station

6.6 MODULAR SURVIVABILITY VEHICLE (MSV) CONCEPT

During the course of this task, it became apparent that the major emphasis of previous escape, rescue, and survivability studies was placed on the definition of escape vehicles. Only minor effort was directed toward defining a minimum capability, operationally flexible, and cost effective survivability vehicle which was free of the penalties associated with escape vehicles such as provisions for de-orbit, earth entry, landing, and recovery.

The 2-man modular survivability vehicle conceived in this study (Fig. 6-8) is cylindrical in shape and consists of three major sections: a forward section in which a docking and viewing port is fitted and in which crew supplies are stored; a center section which provides volu for shirtsleeve crew habitability; and an aft section in which subsystems equipment is mounted. A unique characteristic of this concept is that additional center sections, which are cylindrical shells, can be stacked to accommodate larger crew sizes (Fig. 6-9).

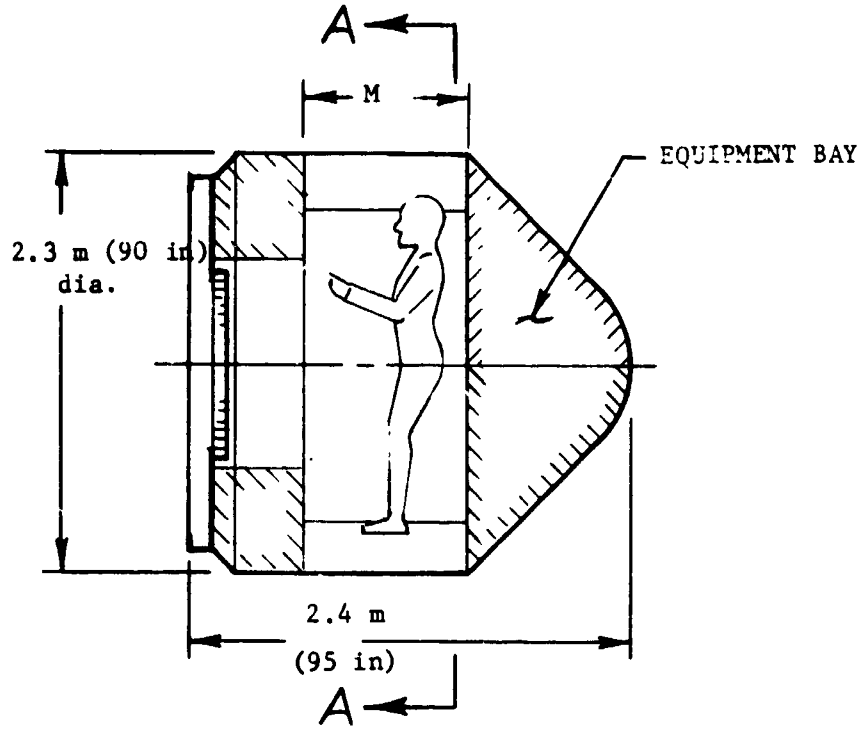
Dimensional analysis showed that a minimum vehicle diameter of 2.3 m (90 in.) is required to facilitate 2 shirtsleeve crewmen in a standing, side-by-side position.

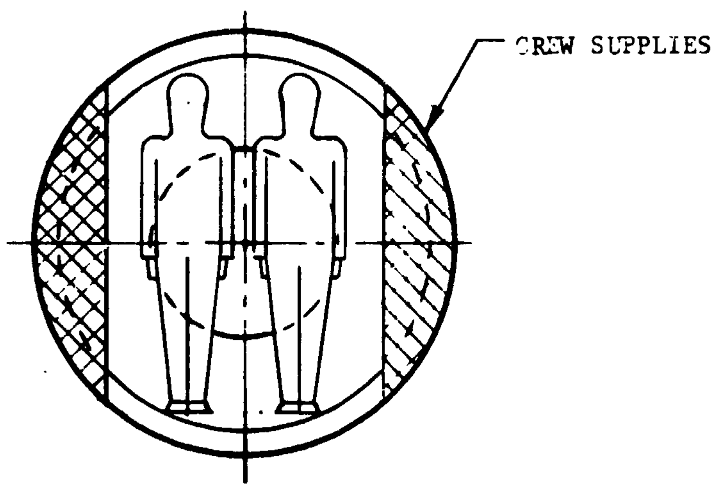
An alternative to the two man across concept is the "four man across" concept, as shown in Fig. 6-3. A minimum vehicle diameter of 2.8 m (110 in.) not only accommodates four shirtsleeve men and is compatible with both the N" and MDAC docking concepts, but also results in smaller vehicle length f r crew sizes greater than two. Because of the fewer sectional elements required to accommodate larger crew sizes, the shorter length within the shuttle cargo bay (Fig. 6-10) and compatibility with both the NR and MDAC docking systems, the four man across concept is preferred.

Subsystems and equipment required for a survivability module are shown in Table 6-2.

A weight summary of the 4-man-ac-oss MSV is shown in Table 6-3, for a 12-man, 2-day capability. The structure consists of a skin stringer frame with a skin thickness of 0.5 mm (0.020 in), resulting in a vehicle primary structural weight of 214 kg (475 lb). Systems weights were obtained from the Aerospace Corporation report (Ref. 21). The total MSV weight, excluding crew, is 1310 kg (2908 lb).

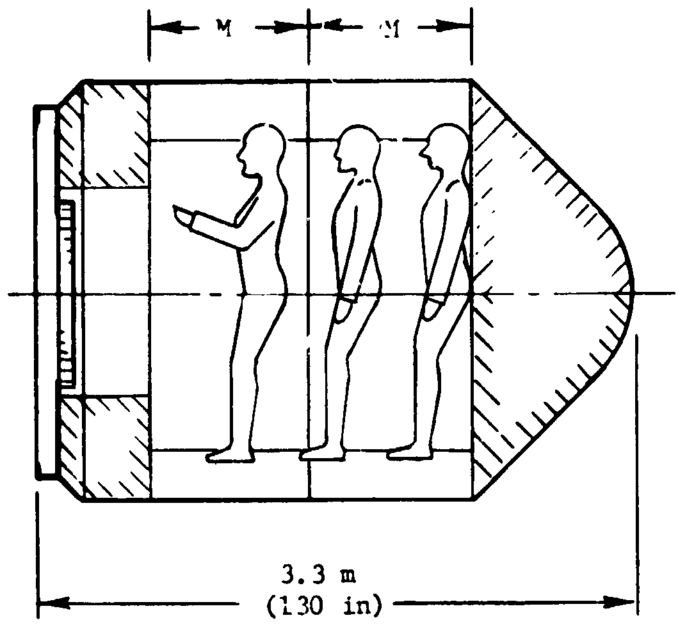
An alternative version would use a simpler monocoque structure with a skin thickness of 2 mm (0.080 in), which results in an additional weight of 80 kg (175 lb) for the MSV.





SECTION A-A

Figure 6-8. 2-Man Modular Survivability Vehicle (MSV)



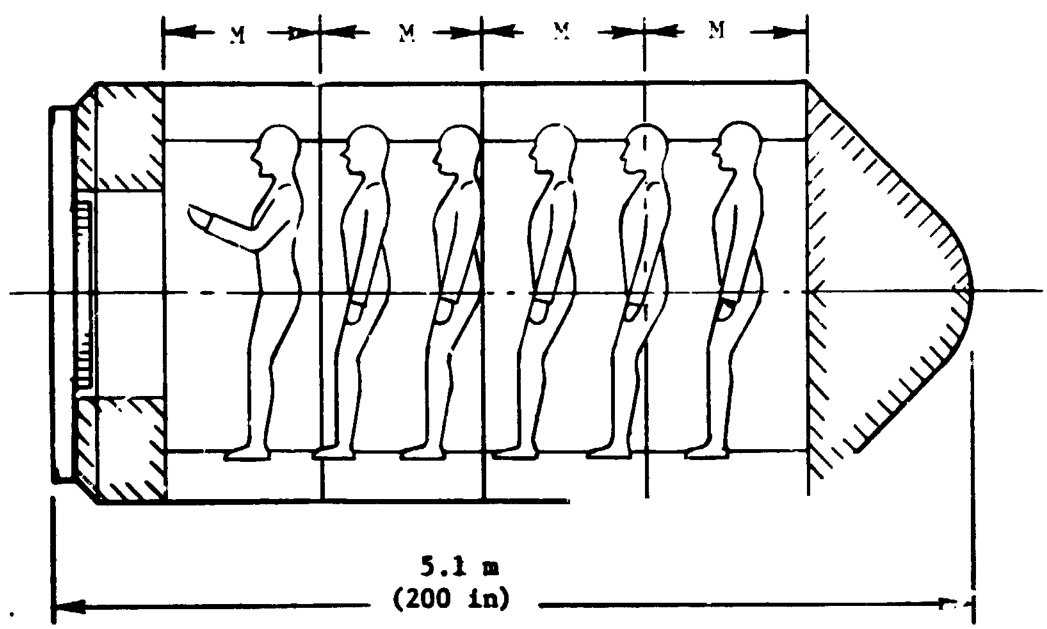


Figure 6-9. Two-Man Modular Survivability Vehicle (MSV) (built up to Six- and Twelve-Man Versions).

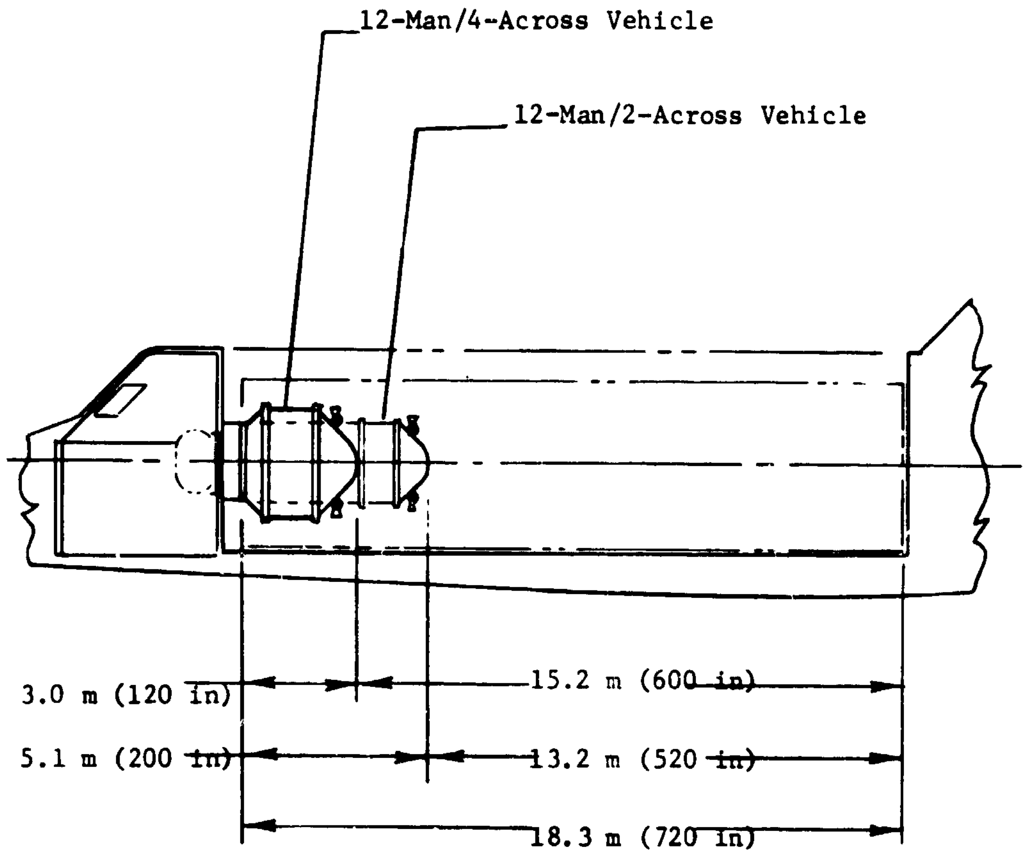


Figure 6-10. Comparison of Two Modular Survivability Vehicle (MSV) Concepts as Installed in Orbiter Cargo Bay

Table 6-2. Crew and Module Operational and Support Subsystems for 4-Man-Across Survivability Vehicle

Function	Method
ECS/LIFE SUPPORT	
Thermal control	Sublimator (H_2O)
Atmos. purification	LiOH + particulate filter
Humidity control	Condensing heat exchanger
Atmosphere	14.7 psi O_2 + N_2
Atmosphere supply	High pressure storage vessel
Atmos. distribution	Ducting + fans
Potable water	Storage tank with bacteria control equip.
Food	Dried - minimal quantity
WASTE MANAGEMENT	
Urine	Collection tube to receiver tank and odor control
Fecal	Bags + storage compartments + odor control
ELECTRICAL POWER SYSTEM	
28 vdc	Silver-zinc batteries (A and B)
Distribution	Wiring/circuit protection devices - general + local
Lighting (internal)	General + local
Lighting (external)	Rendezvous, docking
COMMUNICATION/ISS	
Up/down lines	Voice
Other	Control/display/tracking
Antennas	Rendezvous/docking aid
ATTITUDE CONTROL	
Cold gas system	O_2 TN$_2$ from cabin atmosphere supply tank supply
Control mode	$\pm$ pitch, $\pm$ yaw, $\pm$ roll, no translation, dampen module oscillations, orient module for orbiter approach and docking
DOCKING	
Alignment of mating faces and sealing and latching	Automatic upon module to orbiter contact Orbiter and module remotely separable after crew transfer to orbiter
CREW SUPPLIES	
Sleep	Sleep restraints
Awake	Modified sleep restraints
Other	Minimum hygiene medical supplies, local lighting/adjoining storage compartments
MAIN CONTROL/DISPLAY PANEL	
Viewports (docking)	Monitor, control, command status of: module subsystem, docking, crew subsystem, etc.
MISCELLANEOUS	
Reading material	Varied

Table 6-3. Weight Estimates - Four Man Across Survivability Vehicle
12 Man - 2 Day

	kg	lb
Structure	(390)	(868)
Primary	214	475
Hatch	81	180
Secondary Structure (15% System)	96	213
Systems	(635)	(1418)
S&C, ACS	67	150
EPS	45	100
Communications	18	40
Atmosphere Supply & Control	340	756
Waste Management	27	60
Thermal Control	122	270
Miscellaneous	30	67
Total	1030	2286
20% Growth	206	457
Total Dry Weight	1240	2743
Food, Water	74	165
Total Weight	1310	2908
Delta to Monocoque Structure	+80	+175
	1390	3083

6.7 RENOVATION/MODIFICATION OF APOLLO COMMAND MODULE FOR USE AS AN ESCAPE OR SURVIVABILITY VEHICLE

The potential impact of renovating an Apollo Command Module to function as escape or survivability vehicle, assuming maximum use of existing subsystems is shown in Table 6-4.

Although a new retro-system is shown for escape vehicle applications, it may be possible to achieve the required delta-velocity of approximately 150 m/s (500 f/s) by providing additional RCS propellant tanks within the command module. Present Command Module capability is approximately 27 m/s (90 f/s) and requires approximately 0.24 Kg propellant per m/s (1.78 lb per f/s). This option, could result in considerably lower cost in achieving retro capability.

Table 6-4.

Renovate/New/Modified Items for Refurbished Apollo CM for Use as Escape or Survivability Vehicle

ITEM	Applicability: Escape Vehicle	Applicability: Surviv Vehicle
1. Renovate or replace heat shield	x	
2. Modify CM to 6-man entry capacity (if mission requires)	x	
3. Replace Earth Recovery System (chutes, mortars, fittings)	x	
4. Add new Retro-system	x	
5. Renovate or replace RCS engines	x	x
6. Replace Earth Landing System Crushable ribs (if req'd.)	x	x
7. Renovate or replace Electrical Power System (EPS) batteries	x	x
8. Replace Docking System (CM probe and adapter ring left attached to Lunar Module)	x	x
9. Replace Uprighting System if required (15% probability that it will not be used on landing)	x	
10. Replace G&N exterior mirror lens and prism elements	x	x
11. Renovate or replace G&N optics heat shield	x	
12. Modify Environmental Control and Life Support System (ECLSS) to survivability requirements		x

B

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